Innovative Biological Technologies for Lesser Developed Countries

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Preface

Oversight of the Agency for International Development (AID) is the responsibility of the House Committee on Foreign Affairs. In 1980, under Chairman Clement Zablocki, the Committee requested the Food and Renewable Resources Program of the congressional Office of Technology Assessment (OTA) to review innovative biological technologies that AID could use to help lesser developed countries (LDCs) enhance the productivity of their soils, reduce their need for costly chemical fertilizers, and increase food supplies.

In response to the committee's request, OTA hosted a workshop that brought together some 40 leading scientists, AID representatives, and congressional and executive branch staff for 2 days of presentations and discussions on November 24 and 25, 1980 (see attendees list). On the first day of the workshop each scientist presented a paper about innovative biological technologies and responded to questions. The second day was devoted to discussing AID and its role in using, promoting, and developing innovative biological technologies. Chapters I and II of this report summarize those two days of discussion. Chapters III through XII contain the scientific papers that were presented at the workshop.

These Workshop Proceedings were first released by the Committee on Foreign Affairs in 1981. Continued requests for copies of the proceedings spurred this reprinting. Although the papers have been edited slightly for style, they have not been updated. OTA wishes to thank the authors of the papers, the other workshop participants, reviewers, and the many people worldwide who have requested copies.

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Contents

Chapter	*Page*
I. The Potential of Innovative Technologies	3
II. The Role of the Agency for International Development	23
III. Underexploited Plant and Animal Resources for Developing Country Agriculture (Noel Vietmeyer)	37
IV. Native Plants: An Innovative Biological Technology (Cyrus M. McKell)	51
V. Multiple Cropping Systems: A Basis for Developing an Alternative Agriculture (Stephen R. Gliessman)	69
VI. Development of Low Water and Low Nitrogen Requiring Plant Ecosystems for Arid Developing Countries (Peter Felker)	87
VII. Azolla, A Low Cost Aquatic Green Manure for Agricultural Crops (Thomas A. Lumpkin and Donald L. Plucknett)	107
VIII. Using Zeolites in Agriculture (Frederick A. Mumpton)	127
IX. Agrotechnologies Based on Symbiotic Systems That Fix Nitrogen (Jake Halliday)	161
X. Mycorrhiza Agriculture Technologies (John A. Menge)	185
XI. A Low Fertilizer Use Approach to Increasing Tropical Food Production (William C. Liebhardt)	207
XII. The Gene Revolution (James A. Duke)	227

Chapter I

The Potential of Innovative Technologies

Contents

	Page
Introduction	3
What Do Innovative Technologies Offer?	4
The Workshop's Conclusions	5
Innovative Biological Technologies: Highlights of the Workshop	6
Underexploited Plant Resources	6
Multiple Cropping	7
Agroforestry	8
Azolla/Algae Symbiosis	10
Underexploited Animal Species	12
Zeolites	13
Biological Nitrogen Fixation	14
Mycorrhizal Fungi	17

Chapter I

The Potential of Innovative Technologies

INTRODUCTION

Fertile soil is the key to productive agriculture, whether for an Illinois corn farmer or a subsistence farmer in Ghana, Haiti, India, or other less developed country (LDC). The farmers know this; they know their soil must have good tilth, hold water, and be rich with the necessary nutrients and minerals. They learn these principles through education or, more likely, through tradition and experience. But for most LDC farmers, the old ways of maintaining soil quality may no longer be adequate. Population pressures and rising expectations force them to demand more from the land, to shorten the traditional fallow periods, and to open marginal lands that past generations could avoid using. The farmers may turn to modern agricultural methods—e.g., commercial fertilizers—only to find that the rising costs of these inputs prohibit even this option. This predicament is common throughout LDCs.

Most LDCs, with their growing populations, are concentrated in a belt roughly 30 degrees north and south of the Equator. These tropical and subtropical lands contain diverse ecosystems: mountains, rainforests, semiarid regions, and deserts, and house some 45 percent of the Earth's people. The concentration of LDCs in the Tropics is not a coincidence but stems in large part from inherent physical limitations caused by climatic and soil constraints. As the populations of these nations have grown, many LDCs have come to face a myriad of severe resource problems: degraded soil fertility, deforestation, soil erosion, water pollution, and land-use conflicts. Concomitant social problems—including malnutrition, poverty, and political instability—are common as well.

The humid tropical regions have some of the Earth's most productive ecosystems—lush forests that are the result of eons of long growing seasons and abundant rainfall. But this apparent fertility is often superficial. Tropical forests have been called "deserts covered by trees." In fact, natural soil fertility in the wet tropical latitudes is extremely low because most of the minerals have been leached from the soil by ages of rain and weathering. The nutrients are trapped in the vegetation itself; as the greenery dies and decays on the forest floor, the nutrients are released, then quickly absorbed into new growth.

Arid and semiarid regions face different problems. Lack of water limits the type and amount of crops that can be grown. Wind erosion, salinization, and temperature extremes all work to limit the land's productivity.

Agriculture in tropical latitudes must contend with these and other physical dictates. It must work within increasingly severe economic constraints, too, as the costs of energy, water, equipment, and various other agricultural inputs, from seed to fertilizer, continue to rise.

Conventional agricultural methods, many of which were developed for use in temperate areas, are not wholly suitable for tropical conditions. It is not that conventional agriculture cannot work in the Tropics; it can, in the short run. But without continuous fertilizer inputs, poor tropical soils cannot sustain temperate farming methods. Also, in arid and semiarid regions temperate farming technologies require costly irrigation systems. Thus, with the increasing expense of irrigation development

and fertilizers derived from natural gas, it seems inevitable that LDC farmers will look for new ways to sustain soil fertility and to ensure continued agricultural productivity.

The Agency for International Development (AID) is one mechanism by which the United States can help LDCs meet development and resource challenges. AID has been commended for many of its programs, but it also has been cited for its reluctance to change and for its lack of innovative vision at a time when innovation seems most necessary. This workshop reviewed a number of innovative biological technologies that might help LDCs enhance their agricultural productivity and it takes a special look at the role AID plays, and could play, in developing these technologies.

WHAT DO INNOVATIVE TECHNOLOGIES OFFER?

The innovative biological technologies chosen for discussion in the workshop represent only a sample of the diverse and adaptable approaches being studied by scientists here and abroad. The workshop examined the following:

- *Promoting underexploited plant species, especially native species already adapted to local climates and conditions.* Nature is a storehouse of genetic possibilities including plants with potential as food, fodder, oil seeds, and export goods. Native plants can be integrated into cropping systems, reducing the need for fertilizer and water and enhancing resistance to pests and disease. There is also promise in plant breeding efforts and tissue culture, where native stocks are used to adapt crops to less than ideal environments. This reduces the need to alter the environment with fertilizer, irrigation, and other expensive inputs.
- *Developing multiple-cropping and intercropping systems suitable for specific tropical environments as a way to maximize land productivity.* Multiple cropping is intensive agriculture—growing two or more crops that share space and resources and can produce more per unit of land than monoculture. Proper design of the cropping pattern—e.g., using legumes—ensures and enhances soil quality while providing farmers with a range of products.
- *Designing integrated agricultural systems that take advantage of the special benefits provided by leguminous trees.* Various species of nitrogen-fixing trees (e.g., *Prosopis* and *Acacia*) could be used to revegetate deforested landscapes while providing food, fodder, cash crops, fuelwood, and increased soil fertility. Unlike legumes used in temperate agriculture (e.g., alfalfa), many of these tree species can fix nitrogen under arid conditions.
- *Cultivating "green" fertilizer for rice production.* Azolla, a small aquatic fern native to Asia, Africa, and the Americas, shows great promise as a green manure. The fern provides nutrients and a protective leaf cavity for a strain of blue-green algae, which in turn converts atmospheric nitrogen into a usable form. The nitrogen-rich azolla is grown in rice paddies, either before or along with the rice crop. It also can be harvested and transported to upland fields.
- *Using underexploited animal species to meet local needs for high protein food as well as to provide local populations with innovative cash crops.* For instance, in Peru, guinea pigs are being produced as an unconventional, but tasty and prolific, protein source for local diets. And in Papua, New Guinea, villagers are supplementing farm income by tending an additional garden crop—exotic butterflies for export.
- *Exploring the use of natural mineral soil amendments, e.g., zeolite minerals, that improve soil properties and extend fertilizer efficiency.* Because of their structure, zeolites have unique properties. They

are used today primarily as molecular sieves in industrial processes, but they show promise in agriculture. They seem able to help maintain nitrogen availability in soils and help plants resist water stress. More immediate benefits may show in animal agriculture, where zeolites can serve as feed additives and as decontaminants for feedlot wastes, and in fish farming. Zeolite deposits are thought to be widespread in many LDCs.

- *Reducing the need for commercial nitrogen fertilizer by inoculating suitable crops with beneficial soil bacteria—rhizobia—that biologically take nitrogen from the air and convert it to a usable form for the plant.* Legume rotations, of course, were fundamental to agriculture before the development of commercial fertilizers. These rotations relied on the natural abundance of rhizobia, but improved strains might garner even better results. Legume inoculants are used commercially in U.S. agriculture and suitable strains are being developed for LDC environments.
- *Increasing a plant's capacity to absorb nutrients by encouraging the growth of beneficial micro-organisms—mycorrhizal fungi—that live in association with some plants.* The mycorrhizae significantly increase the root's surface area—the part of the plant that assimilates nutrients from the soil.

THE WORKSHOP'S CONCLUSIONS

Workshop participants shared a general feeling that a range of promising, innovative technologies exists in various stages of development that could help LDCs sustain soil fertility with reduced fertilizer inputs. However, these technologies are underused and many important ones are being ignored by the development community. Many of the innovative approaches discussed are "technologies" in the broadest sense; they are new management systems, not new pieces of hardware.

Research on such innovative techniques generally is underfunded, perhaps because of technological complexity, human reluctance to stray too far from the norm, or well-intentioned skepticism about radically new or unproven approaches to agriculture. Thus, it is all the more difficult to document their worth. Most of the technologies, while promising, need pilot-scale testing in appropriate environments to determine potential problems or necessary alterations before they can be promoted on a wide scale. Also, workshop participants thought that much of the development of innovative technologies is occurring outside of, and perhaps in spite of, the national and international institutions normally considered responsible for maintaining natural resources and for dealing with problems of land quality and productivity.

A particularly interesting facet of these new technologies is that many of them could benefit not only LDC agriculture but also U.S. agriculture by providing opportunities for economic diversification, reducing soil degradation, and bolstering production while lowering capital costs.

No new technology, of course, can be a panacea. The importance of innovation lies in the fact that each new approach increases the number of options available to deal with problems. More choices thus provide increased adaptability to changing social, economic, and physical conditions.

INNOVATIVE BIOLOGICAL TECHNOLOGIES: HIGHLIGHTS OF THE WORKSHOP

This planet is believed to house some 80,000 species of edible plants. Man, at one time or another, has used 3,000 of those for food. But only about 150 plants have been cultivated on a large scale, and less than 20 crops currently provide almost 90 percent of the world's food.

It is clear that mankind could exploit more fully the range of botanical diversity found on Earth. In developing countries, various innovative uses of plant resources show great promise and could help enhance land productivity and increase food supplies. First, it is possible to expand the range of crops grown by using underexploited plant species, especially native species already adapted to local climates and conditions. Second, special attention could be devoted to the potentials of leguminous species, including leguminous trees, that are capable of converting atmospheric nitrogen into a usable form and thus enhancing soil fertility while reducing reliance on expensive commercial fertilizers. Further, innovative and conventional crops could be used together in multiple cropping or intercropping systems designed for specific tropical environments to maximize efficient resource use and land productivity.

The first day of the two-day OTA workshop was devoted to discussions of particular innovative biological technologies—their potential advantages for LDC users and problems limiting their use or development. Here are highlights of those discussions.

Underexploited Plant Resources

Every culture, of course, has indigenous species that have been used traditionally for food, fuel, livestock feed, construction, fiber, medicine, and other purposes either gathered from the wild or cultivated in various small farming systems. But until recently, these traditional crops in LDCs had been lost in the shadows of the Green Revolution and westernized farming techniques.

Now, however, there is renewed optimism about the agricultural potential of many of these plant resources. Native plants can be innovative sources of a wide range of goods—food for people and livestock, fuelwood for cooking and warmth, materials for homes and clothing, even oil seeds and other exports. The benefits provided are compounded because native plants can require fewer total inputs of fertilizer, herbicides, insecticides, energy, and in some cases water. This is because native species are adapted to local environmental conditions—soil type and quality, climate and terrain. Indigenous species often are more resilient to stress, as well; they have evolved defenses for local disease and pest organisms and evolved to be efficient users of available resources, whether water, soil nitrogen, or other necessary nutrients. The native plant concept is a reversal of the old philosophy of using inputs to change the soil to suit the crop. Here the crop is chosen to suit the soil. Examples of innovative plants include:

Winged bean (Psophocarpus tetragonolobus): Generally identified as a "poor people's crop" in developing countries, the winged bean's nutritional potential has been vastly underrated. Actually, this plant, sometimes called a "supermarket on a stalk," has at least six edible parts. The leaves are used like spinach as a vegetable or salad; the flowers are edible, tasting somewhat like mushrooms; the pods, similar to green beans, are nutritious and palatable; the seeds are similar to soybeans and are composed of 17 percent oil and 42 percent protein; the tendrils are also edible and taste like asparagus; and the below-ground tubers contain four times the protein of potatoes.

Amaranth (Amaranthus hypochondriacus): Once the mainstay of certain ancient South American cultures, amaranth is a fast-growing, cereal-like crop that produces high-protein grains in large, sorghum-like seed heads. The grain is also exceptionally high in lysine—one of the critical amino acids usually deficient in

plant protein. Amaranth grain is usually parched and milled to be used for pancakes, cooked for gruel, or blended with other flours. Its leaves can be eaten as a spinach substitute.

Leucaena (Leucaena leucocephala): Of all tropical legumes, leucaena probably offers the widest assortment of uses. It is a fast-growing tree that produces good, dense firewood; it fixes nitrogen in the soil; and its leaves make nutritious cattle forage. This leguminous tree is especially valuable in reforestation efforts.

Any change in the use of fertilizer, pesticides, irrigation, or machinery would depend entirely on the nature of the native plant chosen for cultivation—whether the particular plant could be used on an intensive or extensive basis, the degree to which the plant is susceptible to pests, and many other variables.

Water needs, too, would vary with the specific species chosen for cultivation. Species adapted to tropical soils and moist climates should not require irrigation provided that adequate rainfall occurs during the critical stages of plant development. In regions of less than optimal precipitation, farmers can choose native plants with low water requirements such as jojoba, atriplex, guayule, buffalo gourd, guar, cassia, and acacia species. It is also possible to enhance the effectiveness of water use through management (alternate fallow periods, spaced planting, etc.), water harvesting, and drip irrigation. Where land is not the limiting factor, enhanced water harvesting is showing high potential for fostering plant production under desert conditions. The most suitable plants for these technologies are deep-rooted tree crops, drought adapted species, and biomass plantings.

Some native species also offer hope for intensive agriculture as certain plants could be developed for large-scale operations. If a low-value crop can be replaced with a high-value new crop, irrigation may even be justified. Close plantings, tillage, pest control, and fertilization may then be needed to optimize production and under certain circumstances might be economically viable. Grain amaranth, winged bean, and guar are possible species for intensive development, but many others may be considered.

Equipment and labor needs also vary depending on the specific native plant in question. Some species (e.g., guar or guayule) are amenable to mechanical harvesting. Many others, however, require manual labor, which could be an advantage where excessive unemployment exists.

To develop the potential of native plant resources, more effort needs to be devoted to identifying valuable species and adapting them to modern needs. Once identified, researchers need to look for opportunities to expand the plant's use into similar environments elsewhere in the world. Perhaps a better understanding of the plant diversity available worldwide will lead to more innovation and also an acceptance that folkways are often valid and could be incorporated into a productive compromise between old and new customs.

Multiple Cropping

Multiple cropping is intensive agriculture where two or more crops share space and resources, enhancing both land-use efficiency and long-term productivity. It is not a new technology but rather is at its roots an ancient technique that mimics the diversity of natural ecosystems.

Today's multiple cropping systems vary greatly depending on the character of the site being farmed. In general, multiple cropping systems are managed so that total crop production from a unit of land is achieved by growing single crops in close sequence, growing several crops simultaneously, or combining single and mixed crops in some sequence. Both "sequential cropping," which is growing two or more crops in sequence on the same land, and "intercropping," which refers to various ways of growing two or more crops simultaneously on the land, are included in the broader term "multiple cropping."

Generally, productivity on multiple cropped land can be more stable and constant in the long run than in monocultures. Although each

crop in the mixture may yield slightly less than in monoculture, combined production per unit area can be greater with multiple cropped fields. The overall increased yields result because the component crops differ enough in their growth requirements so that overlapping demands—whether for sunlight, water, or nutrients—are minimal. Multiple cropping, in effect, broadens the land's productive capacity by more fully exploiting the dimensions of time and space.

It is important to point out that not all crop mixtures will produce better yields when multiple cropped. Certain combinations make better overall use of available resources and will be more successful; these crops are considered "complementary." One of the main ways to achieve such complementarity is by varying the crop components temporally—i.e., using sequential planting to achieve a multiple cropping system that avoids antagonistic interactions between the components. Such systems require special management—timely harvesting, the use of proper varieties, alteration of standard planting distances, special selection of herbicides so as not to create antagonisms or residual effects.

Another way of complementing crop components is through intercropping based on relay planting. Direct competition is avoided by planting a second crop after the first one has completed the major part of its development, but before harvest. Research on relay cropping in Mexico and Latin America shows definite yield advantages, especially for corn and beans. The success of relay intercropping depends on the correct combinations of timing and other variables so as to avoid shading, nutrient competition, or inhibition brought about by toxicity produced by the decomposition of previous crop residues. Research in these areas is inadequate.

Finally, farmers can get maximum complementarity in systems where two or more compatible crops are grown simultaneously, either in rows, strips, or mixed fields. For example, traditional corn, bean, and squash systems grown in Mexico show how three species can benefit from multiple cropping. All three crops are planted simultaneously, but mature at different rates. The beans, which begin to mature first, followed by the corn, use the young corn stalks for support. The squash matures last. As the corn matures, it grows to occupy the upper canopy. The beans occupy the middle space and the squash covers the ground. Research shows that the system achieves good weed and insect control. And while the beans and squash suffer a distinct yield reduction, corn yields are significantly higher than in comparable monocultures. It is still uncertain whether the higher yields are the result of more efficient resource use or if some mutually beneficial interaction is occurring among the crop components.

Agroforestry

Agroforestry is a multiple cropping management technology that combines tree crops with food crops, animal agriculture, or both. Like other multiple cropping systems, its goal is to optimize land productivity while maintaining long-term yields. In the past, small-scale traditional agriculture often included trees as part of the farm design, but interest in agroforestry's place in modern agriculture is just beginning. Agroforestry systems can be used to bring marginal lands into production—lands with steep slopes, poor soils, or widely fluctuating rainfall. But tree-crop combinations can also be used on prime agricultural or grazing land to further increase productivity. The main limitations to widespread use of agroforestry practices is lack of knowledge and expertise, and unwillingness in the agricultural establishment to accept the idea of long-term, diversified yields.

The key to multiple cropping's benefits is the intensity of the cropping pattern—drawing as much as possible from the land resource. Despite the intense demands, such systems need not abuse the land; through proper design and operation, multiple cropping management can sustain and actually enhance soil fertility. Depending on the multiple cropping system used, *advantages* can include:

- more efficient use of vertical space and time, imitating natural ecological patterns and permitting more efficient capture of solar energy and nutrients;
- more biomass (organic matter) available to return to the soil;
- more efficient circulation of nutrients, including "pumping" them from deeper soil profiles when deep-rooted species are used;
- possible reduced wind erosion because of surface protection;
- promise for marginal areas because multiple cropping can take better advantage of variable soil types, topography, and steeper slopes;
- less susceptible to climatic variation (especially precipitation, wind, and temperature);
- reduced evaporation from soil surface;
- increased microbial activity in the soil;
- more efficient fertilizer use through the more diverse and deeper root structure in the system;
- improved soil structure, less likelihood to form "hardpan," and better aeration and infiltration;
- reduced fertilizer needs because legume components fix atmospheric nitrogen for themselves and associated nonlegumes;
- heavier mulch cover aids in weed control;
- better opportunities for biological control of insects and diseases because of component plant diversity; and
- potential benefits from mutualisms and beneficial interactions between organisms in crop mixture systems.

But as mentioned, not all crop combinations lend themselves to successful multiple cropping and not all forms of multiple cropping are necessarily good for the land. Sequential cropping, for instance, of two or three crops can actually mine the land of nutrients and minerals if little thought is given to legume rotations, green manures, animal manures, or other fertility-building activities. And in light of the biological and physical aspects of the agroecosystem, other *disadvantages* in multiple cropping might include:

- competition for light, soil nutrients, or water;
- possibility of allelopathic influences between different crop plants caused by plant-produced toxins;
- potential to harm one crop component when harvesting other components;
- difficulty building a fallow period into multiple cropping systems, especially when long-lived tree species are included;
- difficulties in mechanizing various operations (tillage, planting, harvest, etc.);
- increases in evapotranspiration caused by greater root volume and larger leaf surface areas;
- possible overextraction of nutrients, followed by their subsequent loss from the agroecosystem if they are exported as agricultural or forest products;
- damage to shorter plants from leaf, branch, fruit or water-drop from taller plants;
- higher relative humidity in the air that can favor disease outbreak, especially of fungi; and
- possible proliferation of harmful animals (especially rodents and insects) in certain types of systems.

Even though it seems that the biological and physical advantages of multiple cropping outweigh the disadvantages, there also is a range of social and economic factors that would influence the acceptance and use of multiple cropping technologies in various cultures. In terms of social stability, multiple cropping is advantageous because it leads to a diverse agricultural system. Such a system is less susceptible to climatic variation, environmental stress, and pest outbreaks. It is also less vulnerable to swings in crop prices and markets. Multiple cropping also demands more constant use of local labor and provides a more constant output of harvested goods over the course of the year. And because such systems are highly adaptable, they can be melded into many different types of culture without undue stress on existing local customs. Multiple cropping also provides farmers with a large variety of useful products, depending on the type and complex-

ity of their systems. And, of course, multiple cropping systems can reduce the need for fertilizers and other energy imports, thus giving LDC farmers improved economic stability and self-sufficiency.

Reported lower yields, complexity of activities and management, higher labor demands, and difficulty mechanizing operations are all factors that discourage modern farmers from multiple cropping. Conventional agriculture is looking for short-term profits rather than at maintaining constant income over the long term, although it appears that the economics of farming may be changing to favor such innovative systems, especially in the LDCs.

Although there exists the tangible disadvantage of potentially lower yields, most of the disadvantages involved in multiple cropping are derived from lack of experience and knowledge about the workings of complicated agroecosystems.

Azolla/Algae Symbiosis

Rice—one of the most important staple crops in the world—demands rich, fertile soil. But traditional legume crops do not make good green manures for rice farmers; they are reluctant to devote part of the valuable growing season to a relatively slow-growing legume crop. Furthermore, most legume crops cannot grow or fix nitrogen in flooded or waterlogged soils. But these disadvantages can be avoided. Through the use of azolla, a small aquatic fern native to Asia, Africa, and the Americas, rice farmers can produce a fast-growing green manure that thrives in paddy-like conditions.

Azolla is a genus of small ferns that live naturally in lakes, swamps, streams, and other bodies of freshwater. Its tremendous agricultural potential lies in the fact that azolla lives in a symbiotic relationship with a nitrogen-fixing blue-green algae, *Anabaena*. The delicate azolla fern provides nutrients and a protective leaf cavity for the *Anabaena*. In turn, the algae produce enough nitrogen to meet the needs of both plants, plus some extra. Under the right conditions, the fern/algae combination can actually double in weight every 3 to 5 days and fix nitrogen at a higher rate than most legume *Rhizobium* symbionts. In 25 to 35 days, azolla can fix enough nitrogen for a 4 to 6 ton/ha rice crop during the rainy season or a 5 to 8 ton/ha crop under irrigation during the dry season. The nitrogen fixed by the fern/algae combination becomes available to the rice after the azolla mat is incorporated into the soil and its nitrogen is gradually released as the plants decay.

Azolla's value as a green manure for flooded crops has been known for centuries by the people of the People's Republic of China and Vietnam. But its use was relatively limited; few families knew the intricate techniques needed to overwinter and oversummer the sensitive fern successfully, and these families controlled the distribution of starter-stocks in the spring. After the revolutions in China and Vietnam, the new governments eventually recognized the value of azolla and began promoting its use, but their efforts were minimal and progress was slow. It is only recently that worldwide attention has focused on the plant and serious efforts have been made to search for hardier varieties for widespread use.

Azolla's ability to enhance soil fertility occurs both because it is an input of nitrogen and of organic matter. Nitrogen, of course, is a necessary plant nutrient. Humus, the rich organic material formed through plant decomposition, increases the water-holding capacity of the soil and promotes better aeration and drainage. Organic matter also can bind soil particles together, thereby improving the soil structure.

Azolla also can be important in the cycling of nutrients. While it is growing, the plant not only fixes nitrogen but absorbs nutrients out of the water, nutrients that otherwise might be washed away. Some of both the nitrogen and nutrients are stored in the living plant matter until the fern/algae mat is incorporated into the soil and begins to decompose. Because it has a high lignin content, azolla decomposes relatively slowly—6 weeks or more before all the nutrients are released. This natural slow release is ideal for a developing rice crop.

In addition, it seems that azolla suppresses the growth of certain aquatic weeds—in part because the thick azolla mat deprives young weeds of sunlight and in part because the interlocking mat physically inhibits weed emergence. Rice seedlings are not harmed because, when transplanted, they stand above the azolla mat.

Using any green manure crop requires some adjustments in a farmer's crop management system. Depending on the local environments, azolla can be grown as a monocrop, intercrop, or both. If the fern is grown as a monocrop, it is grown and incorporated into the soil before the rice is harvested or it is grown and transported for use on upland crops. Azolla is often intercropped in areas where the growing season is too short for successful monocropping. One method grows two rows of rice planted about 4 inches apart with Azolla growing in two-foot spaces on either side of the double rows. The azolla is incorporated by hand or with a rotary rice weeder. Combining monocropped and intercropped azolla provides nitrogen before transplanting and throughout the growing season. At present, azolla's primary role is as a spring green manure and its secondary role is as a fall manure. It is highly susceptible to pests and temperature extremes and generally is not grown crops in summer.

To be successful, azolla requires phosphorus fertilizer (0.5 to 1.0 kg P/ha/week), but this is not necessarily an increase over the fertilizer needed to produce a rice crop. Rice also requires phosphorus; so, rather than applying it directly to the rice the fertilizer can be given to the azolla in small weekly doses. Once the azolla is incorporated into the soil and begins to decompose, the phosphorus becomes available to the rice crop. Other inputs that enhance azolla growth in certain soils (e.g., potassium) are usually also applied for a high-yielding rice crop and so can be cycled in a similar way.

Water is the primary environmental constraint on azolla cultivation. As a freefloating, aquatic fern, azolla can only grow in areas with abundant, stable water supplies. Although it can last for months under refrigeration, the plant cannot survive for more than a few hours on a dry soil surface under direct summer sun. The azolla varieties available are not very stress tolerant; azolla cannot live in water outside a 0° to 40° range, and for adequate growth the daytime temperature should stay within 15° to 35° C. Humidity and pH also affect azolla growth.

Because the technology to grow azolla from seeds (spores) does not exist, some plants (1 to 10 percent of those needed for startup) must be maintained throughout the year. Because of azolla's sensitivity to temperature stress, the overwintering and oversummering periods are critical. The plant is also susceptible to a number of insect and disease pests. The pests are especially destructive during the summer and must be carefully controlled. In fact, the primary reason why azolla is not cultivated during the summer is because of the destruction caused by rampant insects.

There are also cultural and economic constraints on azolla cultivation. As with any innovation, it can be difficult for people to accept an idea that is foreign to their traditions. The idea of growing an aquatic legume is fundamentally different from most farming societies' norms; and in many hungry countries, the idea of growing a crop just to plow it under seems utterly impractical. Azolla cultivation may be slow in gaining acceptance, too, because it demands a year-round commitment not usually required of rice farmers. And because azolla cultivation is not applicable in areas where rice is broadcast-sown, it is not a viable technology for those regions that do not plant rice in rows.

Finally, social and political factors can work both for and against azolla's use. In some regions, especially where there are unfavorable land ownership patterns, low prices or other strong disincentives, farmers are not willing to shift from their immediate-subsistence, "plant and harvest" approach, because they do not see the long-term benefits. Political systems, too, can have an effect. The successful azolla programs in China and Vietnam depend heavily on specially trained "azolla teams"

made possible by the structure of their farming communes and cooperatives. Societies less centrally organized could have difficulty adopting and transferring azolla cultivation techniques.

One of the major constraints on the development of azolla technologies is simply lack of information. Although it is an ancient agricultural system, its use has always been limited and it has not received much scientific attention. Research efforts are disorganized, scattered, and often repetitious. There has never been an international discussion of azolla research priorities. And once again, traditional segmented research approaches have proven inadequate because many of the problems that remain require a multidisciplinary approach.

As of 1980, azolla was cultivated as a green manure on about 2 percent of the harvested rice area of China and about 5 percent of the spring rice crop. In Vietnam, azolla grows as a winter green manure for 8 to 12 percent of the total harvested area, and about 40 to 60 percent of the irrigated spring rice in the Red River delta. But these two countries are only two of many that might tap azolla's potential. With research, strains could be found that are less sensitive to summer insects and temperature and cultivation could increase substantially. In essence, using azolla in rice production exchanges labor for nitrogen fertilizer. In countries with a shortage of cash but plentiful labor, azolla technology could be a step toward sustainable agriculture productivity.

Underexploited Animal Species

People interested in helping developing countries better their standards of living tend to promote resources and technologies with which they already have experience. One hears much, for example, of how genetic engineering can be expected to make possible self-fertilizing varieties of conventional crops such as wheat and corn. While understandable, this preoccupation with increasing the productivity of "mainstream" species overlooks a vast potential. Indigenous species often have the advantage of being relevant to the customs and values of local people.

Just as there are unfamiliar plants ripe for development as sources of food, feed, fiber, and fuel, so are there also unfamiliar animal species at least as promising. People traditionally have relied on a small number of animals that have been domesticated since prehistoric times. But domestication of some different species could pay tremendous dividends. In some countries, in fact, this is already beginning.

For instance, small animals are particularly suited to domestication in many developing countries because they require little space, they fit well into village or urban life, and they require no refrigeration since they can be eaten in one meal. Moreover, many of these species tolerate the climates of developing countries better than do sheep, cattle, and pigs, and they thrive on readily available diets. Thus, snail farming in Nigeria, giant toad farming in Chile, and guinea pig farming in Peru are all being developed to provide native people with much-needed high-quality protein at affordable costs.

In addition, at least some of these ventures can become the basis of new industries. Thanks to the efforts of researchers at the La Serena campus of the University of Chile, for example, intensive methods have been developed that furnish grocery stores, restaurants, and canneries with 10 to 15 tons of giant toad legs a year. Because the meat is an attractive white and tastes like a blend of chicken and lobster, it could prove to be a lucrative export as well. Giant toads are reportedly easy and inexpensive to rear. Kept in isolated ponds (so that they will not cannabilize other aquatic life) and supplied with insects attracted by flowers, shrubs, and rotten fruit, they require little attention and reach their market weight of about half a pound in 2 years.

The domestication of exotic species is, in fact, already producing foreign exchange for at least one poor country—Papua New Guinea. There, people who used to hunt crocodiles in the wild are now more profitably rearing hatchlings in captivity for the world skin market.

And in remote jungle villages butterflies are being raised on "farms without walls" to meet the rising international demand from museums, entomologists, private collectors, ordinary citizens, and the decorator trade.

Both the crocodile and butterfly projects demonstrate that development and the conservation of natural resources can go hand in hand. They also demonstrate something else: that to succeed, such projects need not only a concern for development but also a sensitivity to local environmental conditions and knowledgeable inputs of science and sociology.

In Papua New Guinea, for instance, the introduction of western-style cattle ranching could threaten the fragile tropical forest ecosystem. And such imported technologies would be completely unfamiliar to local people. By contrast, crocodile and butterfly farming that can be based on sound biological principles, would make it worthwhile for local people to use indigenous renewable resources wisely.

Zeolites

Zeolites are natural, three-dimensional, fine-grained silicate minerals composed of alkali and earth metals crystals that have an ability to separate gas molecules on the basis of size and shape. Over 100 forms have been synthesized and are now the mainstay of multimillion-dollar molecular sieve businesses that are important for industrial purposes in chemical and petrochemical firms in the United States and abroad.

Zeolites, however, also occur abundantly in nature. Almost 50 species have been identified from volcanic sedimentary deposits on every continent. Their widespread dispersion and special properties make them of interest to countries wishing to rely less on costly imported inputs to produce food because they appear promising as a means to improve animal husbandry, fish production, and crop yields. Zeolites have such promise primarily because they act as traps for nitrogen.

Zeolites get their name from the classical Greek words "boiling stones" because they froth when exposed to intense heat. Although their existence has been known to scientists since 1756 and they have been used since antiquity as building materials, their potential agricultural and aquacultural applications were virtually ignored until about 20 years ago. Even now this technology must be said to be suffering from neglect.

When added to animal feed, for example, zeolites have both inhibited the development of mold during storage and increased the growth rates of swine, rabbits, poultry, beef, and dairy cattle. Moreover animals raised on zeolite-enriched rations tend not to be subject to diarrhea or other ills. These minerals are thus a possible alternative to the controversial use of antibiotics in livestock feed.

Besides thriving on zeolite-supplemented diets, animals fed these minerals produce excrement that is at once almost odorless and exceptionally good fertilizer. This is because zeolites capture the ammonia ion from the feces and thus retain the biological availability of the nitrogen in animal wastes. Direct zeolite treatment of manure to reduce odor and improve its efficacy as fertilizer is also feasible, as is using the adsorption properties of natural zeolites to obtain pure methane for energy purposes from animal or other organic wastes.

In summary, the application of zeolites to animal husbandry holds some promise from the perspectives of livestock production, pollution control, crop yields, and energy alternatives.

Zeolite technology also has potential for the commercial fish breeding and farming. For one thing, the rations now fed to fish in such enterprises are quite expensive. As the nutritional requirements of fish are similar to those of poultry, the indications are that zeolite supplements could be expected to reduce feeding costs. For another, many fish species are raised in closed or recirculating water systems where the accumulations of nitrogen from their waste and the decay of uneaten food commonly causes sterility, stunted growth, and high mortality. Although various means already are used to deal with these problems, zeolite regulation

of the nitrogen content of fish ponds has been reported to be cheaper and, under low temperature conditions, more reliable.

Similarly, the affinity of zeolites for nitrogen may be important in ponds and small lakes where eutrophication results in an oxygen-poor environment detrimental to fish life. Evidence suggests that the ability of these minerals to introduce free oxygen into stagnant water might increase the number of fish that can be raised or transported in a given volume of water.

The properties of zeolites also improve the performances of chemical fertilizers and pesticides, fungicides, and herbicides. For example, zeolite-treated soils retain the nutrients supplied by chemical fertilizers longer than soils treated with the fertilizers alone. The presence of zeolites as soil conditioners (also known as soil amendments) also has been found to regulate the release of critical nutrients from fertilizers. Improved yields of wheat, apples, eggplant, carrots, sorghum, radishes, chrysanthemums, and sugar beets have been reported.

Controlled release of micronutrients from the soil itself—e.g., iron, zinc, copper, manganese, and cobalt—has also been found when zeolites are used in conjunction with chemical fertilizers; this also prevents them from caking and hardening during storage.

Zeolites added to pesticides, herbicides, and fungicides seem to enhance their effectiveness. They can also be exploited to remove toxic heavy metals from the soil, thus preventing the toxic wastes from moving up the food chain from plants to animals and, ultimately, to people.

Nonetheless, the commercial use of zeolites in agriculture has generally been on only a relatively small scale and then predominately in Japan and other parts of the Far East. Even though a number of domestic companies have undertaken preliminary zeolite studies, little information is available on the long-term benefits or adverse impacts of these minerals on food production or the environment. Furthermore, even such information as has been developed is often proprietary. Though the desire of the private sector to keep its data confidential is understandable, this cannot help but lead to duplication of effort and slow progress.

Developing countries of course would be eager to reduce their costly dependence on imported fertilizers, fuels, and livestock feed. Cooperative ventures between the United States and these countries could improve knowledge of zeolite technology and, importantly, undertake long-term or large-scale testing projects under field conditions.

Biological Nitrogen Fixation

One very promising multiple cropping strategy is the use of leguminous plants. Legumes can provide food, livestock fodder, and wood while concurrently improving soil fertility. Leguminous plants—e.g., temperate species such as alfalfa, soybeans, and clover—have the capacity to provide their own nitrogenous fertilizer through bacteria (Rhizobia) that live in nodules on their roots. The bacteria chemically convert atmospheric nitrogen into a form that the plant can absorb and use. The nitrogen also is available in the root zone for nonleguminous companion or follow-on crops to use.

The use of legumes is not new; generations of farmers relied on rotations of legume plants to restore nitrogen in the soil long before the advent of cheap commercial fertilizers. Now, as energy costs skyrocket and fertilizer costs become prohibitive in many developing countries, legume use—green manure—may be the best remaining option for maintaining soil fertility and agriculture productivity.

Leguminous species could not only help protect LDCs from burgeoning energy costs but could also improve local nutrition. Nutritionally, legume seeds (beans or pulses) are two to three times richer in protein than cereal grains. Many have protein contents between 20 to 40 percent. A few even range up to 60 percent. This is particularly important because there is chronic protein deficiency in virtually every developing country.

Inoculant Technologies: Nitrogen can be converted into forms usable by plants through industrial processes, but only at great cost, especially as energy prices escalate. But biological nitrogen fixation (BNF) by symbiotic associations of plants with micro-organisms may be an economically and environmentally sound approach to sustainable agriculture.

Farmers can capitalize in two ways on certain plants' innate ability to fix nitrogen biologically. First, of course, like countless past generations of farmers they can use legumes in their cropping systems and benefit from the nitrogen produced. But recent innovations also can help farmers maximize nitrogen fixation. Using inoculant technology, selected legumes can be inoculated with specific strains of Rhizobium, the soil bacterium that associates with legume roots and fixes nitrogen. This way farmers can more fully exploit the plant's fertilizing capabilities.

Most soils harbor various native rhizobial populations and these strains will associate with sprouting legumes. But because these strains differ greatly in their effectiveness, it can be to the farmer's advantage to plant legume seeds that have been inoculated with proven strains of Rhizobium. The objective of inoculation technologies is to introduce sufficiently high numbers of preselected strains of rhizobia into the vicinity of the emerging root so that they have a competitive advantage over any indigenous soil strains of lesser nitrogen-fixing ability.

Commercial-scale inoculant use is common in the United States and Australia. Brazil, Uruguay, Argentina, India, and Egypt also produce inoculants. But while demand for inoculants is growing in many countries, it is not enough to simply import U.S. or other inoculants because they may not be suitably adapted to the LDCs climate, soils, and farming systems. BNF can be improved by selecting effective Rhizobium strains from the local environment and culturing these.

The major scientific constraint on developing BNF technologies is inadequate understanding of the interactions among specific host legumes, rhizobial strains, and various environments. This results in an inability to predict whether a given legume will respond to inoculation in a particular region. A lack of trained personnel in tropical regions also acts to limit research and development efforts. And because inoculant development and use requires some technical training, it may not be an easy technology for LDCs to adopt widely. But while legume use holds potential in all segments of agriculture, inoculant technology at present should only be advocated when there is a known need to inoculate.

Most legumes in the Tropics fix about 100 kg/ha/yr of nitrogen, although the forage tree leucaena can fix as much as 350 kg/ha/yr and some other species can fix as much as 800 kg/ha/yr. However, the benefit to nonlegumes is small when compared to the effects of nitrogenous fertilizer as applied in the intensive cereal production systems of the developed world. It is unrealistic to think that biologically fixed nitrogen will replace commercial fertilization of cereal and root crops. These crops are known to respond to levels of nitrogen far in excess of those that could currently be supplied through legume BNF. Thus, it would be profitable to determine ways to increase the contribution of legume BNF as a complement to nitrogen fertilizers rather than as an alternative.

Although legumes seem unlikely to replace commercial fertilizers, fertilizer savings through the use of legumes could represent a significant savings in foreign exchange, reduce dependence on energy-rich nations, and lend more stability and diversity to LDC agriculture.

Leguminous Plants: A great variety of leguminous plants—both food crops and species useful for fuelwood, fodder, and other needs—exist that could be cultivated in moist and arid/semiarid tropical climates. Winged bean is one extraordinarily valuable leguminous species. Tarwi, tepary bean, and yam beans are also nitrogen-fixing species with potential in moist tropical environments.

But not all leguminous species have high water requirements. Adapted plant species

could be used in arid and semiarid regions as well, serving not only to enhance land productivity but also to stimulate depressed economies. For example, leguminous trees such as *Acacia, Leucaena,* and *Prosopis* could be important, fast-growing fuelwood sources. Because 80 percent of the wood consumed in the Third World is used as fuel, and wood shortages are of crisis proportions in some areas, the potential of agroforestry should not be underestimated.

In arid/semiarid regions, of course, water availability is a key factor in agricultural productivity. But problems are compounded in some dry environments because soils also have low fertility. In these areas, drought-adapted, deep-rooted, nitrogen-fixing tree species (e.g., *Acacia albida* and *Prosopis cineraria*), perennial arid-adapted herbaceous legumes (e.g., *Zornia* and *Tephrosia*), and shrubby legumes (e.g., *Palea* species) could increase soil fertility and triple water use efficiencies. By bolstering soil fertility with tree species, it is possible to create a system where production of food staples is water-limited rather than fertility-limited. And intercropping traditional, annual food staples such as millet, sorghum, groundnuts, and cowpeas with leguminous trees can actually stimulate crop yields.

Livestock fodder and cash crops, too, can be obtained from arid species. Arid-adapted, salt-tolerant shrubs (e.g., saltbush—Atriplex species), the pods of leguminous trees (e.g., *Acacia tortilis, Acacia albida,* and *Prosopis* species), and even cactus (*Opuntia* and *Cereus*) can expand the amount of forage available for local livestock while improving soil quality and enhancing the stability of the grazed ecosystems.

LDC farmers also could benefit from growing perennial, arid-adapted plants as cash crops. The species Jojoba is under development in southern California, Arizona, Mexico, and various semiarid LDCs. It produces seed that contains a rancidity-resistant, nonallergenic, liquid wax with lubricating properties equivalent to oil from the endangered sperm whale. Another desert plant, guayule, contains natural rubber and could become a major semiarid crop. Other potential lies with various species of drought-adapted leguminous trees that might be useful for the gums they exude, cacti that produce table-quality fruits, and a number of other innovative plant resources.

Surprisingly, relatively little work is being done to further current knowledge about some of these highly promising plant resources. But as energy, fertilizer, irrigation, and other costs escalate, it seems inevitable that farmers in arid and semiarid regions will look more to adapted crops.

Optimal water-use efficiency in an arid/semiarid agroecosystem demands a mix of nitrogen-fixers and water-to-dry matter conversion specialist plants. For instance, cacti are a better supplier of the energy portion of livestock feed than legumes because they have a fivefold greater efficiency converting water to dry matter. However, legume leaf litter is important to create good soil fertility so the cactus can achieve its maximum water-use efficiency. Thus, a mix of plants is needed. And because livestock need both energy and protein, both energy- and protein-producing plants are required.

Similarly, appropriate use of arid-adapted legumes can increase fertilizer-use efficiency. Adapted legumes do not require nitrogen themselves and when properly incorporated into a diversified agroecosystem they will reduce nitrogen needs for nonlegumes as well. Many arid-adapted plants, both legumes and nonlegumes, have very deep root systems—an advantage because they are thus capable of extracting nutrients and minerals from deep subsurface soil layers. Also, the deeper rooted species should capture a higher portion of any fertilizers applied because the nutrients are not as likely to leach beyond their deep root zone. As an added benefit, wind and perhaps water erosion might be reduced, as many of these plants are perennials and thus keep the soil more adequately protected.

There are no major scientific constraints to using arid-adapted plant resources in LDC agriculture, but there is great need for expanded research and development efforts. The poten-

tial paybacks could be great. Environmental impacts, too, are overwhelmingly positive, including the potential to slow desertification.

Politicial and social constraints, however, exist that might limit the use of innovative plants. Cultural traditions, for instance, are not easily changed and innovation must blend into existing values systems and local behavior. If, as in Sahelian Africa, free-roaming goats devour young tree seedlings because tradition allows that goats can forage unrestrained, then reforestation attempts must consider this and devise goat-proof protection for the young trees.

Other social influences also can make the acceptance and use of innovation all the more difficult. This is especially clear in research centers run by scientists either from or trained in developed countries; consciously or not, they often strive to promote their own cultural values and ignore the methods and effectiveness of native farming systems. As was the case with *Acacia albida,* the scientists may not be broadly trained—the agronomists failing to see the tree's food potential and the foresters underestimating its potential because it does not grow in forests and hence is not part of standard sylviculture concepts. It is not lack of concern that causes this problem. Rather, some agricultural scientists tend to be overspecialized and limited in their experience. Also, administrative structures often thwart attempts to develop integrated, innovative programs.

In practical terms, such innovative biological technologies offer real hope for LDC farmers. And the scale need not be big. A farmer, for instance, could plant 1 hectare with 200 *Prosopis* trees at 15 cents each for a total cost of $30. Land, a shovel, and buckets for watering the seedlings are the only prerequisites. With protein and nitrogen contents of 12.5 and 2.0 percent, respectively, pods from the trees could in 2 or 3 years produce 60 kg of nitrogen and return the $30 initial investment.

Many of the innovative systems now receiving attention from the scientific community are actually widely used by subsistence farmers in the developing countries. However, the plants under cultivation now are of unselected genetic stock. It is comparable, in fact, to the use of unselected races of maize and wheat that were in use in the late 1800s in the United States and Europe. Subjecting the innovative species to a rigorous research and development effort could be expected to produce yield increases—perhaps twofold and threefold in 15 years—and other beneficial refinements of immense value to the people of the Third World. And yield increases in tree legume production, fuelwood production, cash crop production, soil fertility, and ensuing staple food production would have repercussions throughout the economy—more income; greater demands for goods; a larger tax base to support roads, schools, and health services; and increased employment. By working within the bounds of the ecosystems, innovative plant resources can help agrarian societies ensure sustainable and stable agriculture.

Mycorrhizal Fungi

Nitrogen is only one of the nutrients essential to plant growth. So another approach to enhancing LDC agriculture without inputs of commercial fertilizers is to find ways to increase the effectiveness of the plant's use of the other nutrients available in the soil.

Selective plant breeding, of course, still holds great potential for developing varieties of innovative and traditional crops that are more resistant to environmental stress. Geneticists have made extraordinary strides in breeding varieties that respond to commercial fertilizer inputs; similar efforts could help locate and develop plants that would grow and prosper under less than ideal conditions—marginal lands, variable climates, or deficient soils. This potential amplifies the importance of preserving native plant resources, both in seed storage facilities and in their natural habitats, because geneticists necessarily turn to hardy, native stocks as sources of genetic material to improve cropped varieties.

There is another "biotic fertilizer" that might aid LDCs in their quest for sustainable agro-

ecosystems. Mycorrhizal fungi are beneficial soil fungi that live symbiotically with a vast range of plants. Mycorrhizae are the structures formed—part plant, part fungus—by the symbiosis. These structures can extend up to 8 cm from the root into the surrounding soil, providing a bridge to transport nutrients back to the roots. The host obtains nutrients via the mycorrhizal fungi, while the fungus obtains sugars or other foods from the plant. The association results in a marked increase in the host plant's growth.

There are many species of mycorrhizal fungi that form mycorrhizae and can enhance plant growth. These fungi are so common, in fact, that literally any field soil sample from the Arctic to the Tropics will contain some. The most common type, vesicular-arbusula (VA) mycorrhizae, occur on liverworts, ferns, some conifers, and most broad-leaved plants including agronomically important species such as wheat, potatoes, beans, corn, alfalfa, grapes, date palms, sugar cane, cassava, and dryland rice. Only 14 plant families are considered primarily nonmycorrhizal.

The fungi essentially increase the surface area of the plant's roots for absorbing nutrients. They actually can increase the plant's absorptive area by as much as 10 times. The fungi also extend the host plant's range of uptake; nutrient ions that do not readily diffuse through the soil—e.g., phosphorus, zinc, and copper—can be tapped from beyond the normal root zone by the fungi. Absorption of immobile elements can be increased by as much as 60 times by the plant-fungi symbiosis. Perhaps the most important benefit provided by mycorrhizal fungi is increased phosphorus uptake. They also stimulate plant absorption of zinc, calcium, cooper, magnesium, and manganese. Plant uptake of mobile soil nutrients such as nitrogen and potassium is rarely improved because normal soil diffusion typically supplies adequate amounts of these regardless of root size.

Mycorrhizal fungi also can enhance water transport, prevent water stress under some conditions, enhance salt tolerance, and increase symbiotic nitrogen-fixing bacteria such as Rhizobium.

The potential offered by mycorrhizal fungi as biotic fertilizers, however, is not as vast as it might seem. Mycorrhizal fungi already occur in most soils and thus already grow in association with most agronomic crop plants. Because these fungi are so widespread, immediate needs for inoculation are limited. The inoculants currently available are for use on disturbed sites (strip-mined areas where indigenous mycorrhizal populations have been destroyed), on fumigated soils (any forest or crop nursery or plot that has been treated to remove soil-borne pests), and in greenhouses (because sterile soils lack native mycorrhizal fungi). In these situations, inoculation with mycorrhizal fungi has proven beneficial—e.g., in fumigated sand or soil, VA mycorrhizal fungi will increase the growth of citrus, soybeans pine, and peaches. Growth improvements also show in cotton, tomatoes, corn, wheat, clover, barley, potatoes, and many other crops.

But even though large-scale field inoculations with mycorrhizal fungi are rare because of adequate indigenous populations and because there is limited inoculum available, it seems likely that such applications might be much more valuable if, for instance, scientists develop mycorrhizal fungi inoculants that are superior to native populations. Because many indigenous mycorrhizae are relatively inefficient symbionts, improved strains of fungi could enhance plant growth, even in nonsterile soils. And because huge expanses of tropical soils (e.g., the Brazilian Cerrado) are either deficient in phosphorus or immobilize added phosphorus fertilizers, mycorrhizal fungi could improve the productivity of the marginal lands, if fungi having the ability to extract small quantities of fertilizer were developed and added to the soil.

Even though mycorrhizal fungi inoculants are used commercially in some circumstances, their importance is limited and many questions about their effectiveness remain unanswered.

For instance, fumigating fields with methyl bromide, a biocide that is extremely toxic to mycorrhizal fungi, often is followed by stunted growth in following crops. Yet little work has been done to determine the feasibility of field-scale application of inoculants. And even in nursery crops grown on sterile, nonmycorrhizal soils, inoculations receive limited use in part because detailed information regarding their value is lacking. For tree crops, however, some of the answers may be coming; the U.S. Forest Service is conducting a testing program using commercial inoculum on tree nursery sites throughout the country. When the tests are complete they should indicate the commercial feasibility of producing and using mycorrhizal inoculum in fumigated tree nurseries.

Three major obstacles hinder further development of this biotic fertilizer. First, no large-scale field experiments using mycorrhizal fungi under normal agricultural conditions have been conducted, yet such work is a necessary forerunner to actual use of the fungi. Second, cost-benefit analysis is warranted to determine the economics of mycorrhizal applications. And finally, agriculture itself must shake loose of some conventionality; it seems locked to practices for increasing soil fertility that only involve use of commercial chemical fertilizers.

Because mycorrhizal fungi increase the efficiency of fertilizer use, they can be thought of as biotic fertilizers and might be substituted for some fertilizer components. Considering estimates that 75 percent of all the phosphorus applied to crops is not used within the first year and thus reverts to forms unavailable to plants, especially in tropical soils, it appears that further work on improving mycorrhizal fungi effectiveness could aid LDCs in developing sustainable agricultural systems.

Chapter II

The Role of the Agency for International Development

Contents

	Page
Introduction	23
Budget and Goals	23
Current Innovative Biological Activities at AID	24
Two Approaches to Apply Innovative Biological Technology to LDC Agricultural Problems	25
The Need for Cooperative Ventures	26
The Need for Field Demonstrations	26
The Need for Innovative Research	26
The Need for Flexibility	27
The Need for Trained AID Staff	28
Perceived Constraints	28
Mission Agricultural Activities	28
CGIAR	28
Agricultural Staff	29
Summary of Workshop Suggestions	30
AID Organizational Changes	31
List of Attendees	32

Chapter II

The Role of the Agency for International Development

INTRODUCTION

During the second day of the workshop, AID staff reviewed their agency's agricultural development activities and the various constraints under which AID operates when carrying out its agricultural mandates. Their discussions were candid and are summarized in the following text. An organizational chart in effect for AID in November 1980 appears at the end of this chapter.

BUDGET AND GOALS

In 1980, AID carried out about $600 million in agricultural projects and research related to solving agricultural problems and developing agricultural opportunities in LDCs. Further, AID spent an additional $43 million to transfer fertilizer, much of it going to Sri Lanka, Zambia, and Bangladesh.[1] During the first quarter of FY '81, fertilizer transfers to India, Kenya, Zambia, and Bangladesh were $105 million. AID's main thrust in agriculture is to help LDCs increase agricultural productivity, especially of the locally accepted basic food crops. By doing so, AID's goal is to help LDCs improve their economy, nutrition, and the general well-being of their people.

But for AID to step beyond traditional approaches and promote innovative technologies to solve LDC food and agricultural problems is risky. AID is not a research agency; its goal is development. Therefore, AID commonly supports research that holds promise of high immediate payoff and tends to avoid research that may have long-run payoffs. Similarly, AID feels that its development projects should focus on the short term, have high visibility, and show positive results quickly. It is not surprising that some AID agriculturalists believe that "when you only have $2 to bet you don't go for long shots." To compound the problem, AID's small budget for innovative activities is often one of the first targets during budget cuts.

The United States, on the basis of its gross national product (GNP), in 1980 ranked 14th of those countries that provide development assistance to LDCs. For example, Sweden contributes 1.0 percent of its GNP whereas the U.S. contributes 0.19 percent.

AID's budget dilemma is complicated further by a growing list of competing development needs such as forestry, women-in-development, and environmental concerns. AID has been many things to many people, but it has not been perceived by Congress as a technical transfer agency. AID stressed that there remains a lack of understanding among the public and Congress about how science and technology relate to economic development.

[1] AID's financed fertilizer purchases for FY '80 were at the lowest level since 1965.

CURRENT INNOVATIVE BIOLOGICAL ACTIVITIES AT AID

During the workshop, AID participants presented a brief overview of some of their current activities involving various innovative biological technologies. Examples included biological nitrogen fixation, tissue culture, and applied soybean research. In addition, through a collaborative effort, AID, the Joint Research Committee (JRC), the Board on International Food and Agricultural Development (BIFAD), and 30 land-grant colleges and universities have developed three Collaborative Research Support Programs (CRSP) to study small ruminants, sorghum and millet, and bean/cow pea production systems. The activities involve 30 U.S. universities, six international agricultural research centers, and one foundation. Work is carried out at 28 LDC sites with collaboration of the local LDC institution. Two new CRSPs are being developed in nutrition and soils. These activities will expand the number of participating U.S. universities by eight and LDC sites by ten.

CRSPs are viewed as long-term research endeavors, at least five years in duration. AID funds up to 75 percent of the CRSP and the collaborating U.S. colleges and universities contribute from 25 to 50 percent. At least 50 percent of AID's CRSP budget is spent in participating countries. AID's minimum budget for FY '82 CRSP activities is $11 million. AID plans to invest a minimum of $88.3 million in CRSP activities from FY '82 through FY '87.

Biological nitrogen fixation (BNF) is not a new technology; it was recognized in Biblical times that when certain legumes were grown in alternate years, the yield of the following year's crop was improved. After five years of research, AID recognizes that BNF technology still could be improved. Because it can provide nitrogen to plants in a usable form without the expense of commercial nitrogen fertilizers, it has important potentials for LDCs and developed countries alike.

Rhizobia, nitrogen-fixing bacteria that live in nodules associated with the roots of certain plants, can be used in some instances to inoculate the roots of plants to enhance nitrogen production. No infallible technique to inoculate seeds is known, but this is an area of research AID is addressing. (The information of BNF summarized elsewhere in this report is based on research at the University of Hawaii sponsored in part by AID). BNF in tropical grasses also is being studied. AID is working on in-country testing of BNF technology, building inoculation production and distribution systems, developing profitable BNF cropping systems, and providing continued help in improving BNF technology for LDC use.

AID believes that commercial fertilizers play an important role in LDC agriculture but also believes that BNF technology can help these countries reduce their need for commercial nitrogen fertilizers. Considering that commercial nitrogen fertilizer may cost as much as $1 a pound by the year 2000, BNF, which ultimately may reduce the need for commercial nitrogen fertilizers in LDCs by 25 percent, could help tremendously.

AID is supporting some research on tissue culture to supplement its traditional research on standard crop-breeding practices. AID believes tissue culture to be an inexpensive technology and one that has good potential for use in LDC agriculture.

In the past, agriculturalists selected superior plants for reproduction by handpicking those few individual plants having certain desirable characteristics out of many thousands of the less desirable specimens. Space and time severely limit the number of plants screened this way. With tissue culture, desirable plants can be selected and propagated quickly and easily. For example, an agriculturally desirable plant can be used as a cell source for a desired special characteristic such as salt tolerance needed for growth in irrigated areas. A tiny slice of the plant can be used to grow large clusters of cells that can be separated in the laboratory and screened to find the cells having the required characteristics. These cells in turn can be grown to full plants that themselves

can be used for seed sources. Research has demonstrated that the new plants will survive the particular soil stresses for which they were screened. This technique enhances our ability to design plants for the especially harsh environments in LDCs and holds real promise for improving LDC agriculture.

AID provides support for the International Soybean Program (INTSOY) as part of its effort to support innovative biological technologies. INTSOY works to improve and adapt soybeans for tropical developing countries through germplasm selection. Some of their applied research deals with finding improved ways to store seed for extended times in LDCs and improving soybean processing using simple technologies. INTSOY also is studying the role of soybeans in the LDC farming economies and in the national economy as well.

TWO APPROACHES TO APPLY INNOVATIVE BIOLOGICAL TECHNOLOGIES TO LDC AGRICULTURAL PROBLEMS

Two sharply different approaches to applying innovative biological technologies to LDC agricultural problems, particularly the problem of rising fertilizer costs, surfaced during the workshop's discussions. The first might be called an "agroecosystem approach" and was stressed by most non-AID participants. The second reflected a "conventional production approach" and was mainly an AID viewpoint.

The "agroecosystem approach" focuses on applying biological technologies that are tailored to fit the biological, physical, and social limitations of the local environment so that sustainable agriculture can exist within the constraints of the natural resource base. This approach includes a concern for energy conservation and a desire for interdisciplinary research and development.

The "agroecosystem approach" to LDC requirements for food, fodder, and fuel also focuses on developing new agricultural systems and on accepting rediscovered, and perhaps improved, agricultural systems. A wide spectrum of agricultural crops is considered including a number that might be viewed as nontraditional. This approach emphasizes restoring, maintaining, and improving the natural resource base while offering the farmers a reasonable chance for economic betterment.

In comparison, the "conventional production approach" stresses production and increased yields. It tends to focus on a more limited number of crops for which a market already exists. The ecosystem is adjusted to provide high production of these crops by using intensive inputs of commercial fertilizers, pesticides, pumped water, and petroleum-powered farm equipment. Some such systems commonly are categorized as "green revolution" technologies. Major efforts have been devoted to mainstay crops such as rice, corn, sorghum, and soybeans, and production increases generally have been outstanding.

The variety of crops dealt with in this approach is more limited than in the "agroecosystem approach" and monocultures often are economically advantageous. Production efforts typically attempt to foster crop growth by overcoming local environmental constraints such as infertile soils or water scarcity. In many cases the technologies promoted are adaptations of technologies that have been used successfully in developed countries and temperate climates.

There are, of course, instances where the two approaches overlap, but these are exceptions. Proponents of both approaches are trying to help LDCs improve the well-being of the populace—their methods, however, include quite different agricultural styles and practices. The workshop focused on the opportunities shown by each of the approaches for helping LDCs reduce their need for expensive commercial fertilizers while enhancing soil productivity.

The Need for Cooperative Ventures

Participants agreed that agricultural research and its appropriate implementation in lesser developed countries is an AID/LDC cooperative venture and that good communication is essential for success. They discussed the inherent difficulties involved in using U.S. expertise in LDC projects because many U.S. experts lack the special training that is appropriate to the physical and biological environment. Many U.S. technical experts used by AID are drawn from U.S. land-grant universities and consulting firms where there is little familiarity and experience with LDCs. And because the United States historically has little experience in LDC—i.e., tropical—agriculture, AID has difficulty finding contractors who are able to grasp LDC agricultural problems quickly and recognize the appropriateness or inappropriateness of temperate region agricultural solutions.

AID has provided grants and other support to numerous U.S. universities to help them develop their teaching/research expertise so that it can be tapped to help solve LDC agricultural problems. Many of these universities have set aside land for use in agricultural research and teaching, but again agricultural research results commonly are not readily transferable from region to region. Further, because pilot studies often are cumbersome to conduct, take considerable time, and lack significant recognition, few university scientists are eager to devote effort to projects relevant to LDC agriculture, even though certain aspects may also hold indirect promise for improving U.S. agriculture.

The Need for Field Demonstrations

Pilot projects, demonstrations, and field experiments carried out in LDCs by U.S. and host-country interdisciplinary teams on innovative biological technologies are essential first steps before new technologies can be used widely. Section 103A of the Foreign Assistance Act directs AID to carry out pilot studies. Further, workshop participants agreed that the private sector, whether U.S. or LDC, should be encouraged to participate in biological technology development and its transfer to potential users. Only where new technologies can be shown to be economically profitable is there the likelihood of their being pursued and adopted by the private sector. For example, Thailand established several innovative programs in alcohol production from cassava through direct links between the private sector and Thai research institutions. It was also pointed out that in many places, farmers learn new agricultural techniques from salesmen.

AID believes that during the 1980s it will emphasize technology transfer but hopes to sponsor increased adaptive field research and do cooperative research with LDC scientists. The Agency sees the need for multitiered development efforts but recognized the difficulty in coordinating them. There is an acute need for LDCs to establish their own national research priorities rather than having the donor community do so.

Pilot-scale activities that receive partial support from AID do exist at the international agricultural centers. But whether or not all such institutions strongly emphasize the "agroecosystem approach," especially agricultural techniques that are aimed at enhancing soil fertility *and* reducing reliance on expensive commercial fertilizers, was debated. AID believes that much of the work carried out at the international centers is innovative, but many of the non-AID participants felt that these centers pay little attention to low fertilizer, low-energy agricultural systems.

The Need for Innovative Research

Further, AID was criticized for spending $43 million of its $650 million agricultural efforts on the transfer of expensive commercial fertilizers to LDCs without providing incentives to try new agricultural methods that minimize fertilizer use. LDCs must develop the resources to continue appropriate fertilizer use, but along with this should go development of efficient new agriculture systems that rely on biological processes to complement soil nutrient availability. The use of mycorrhizal technologies,

for instance, seems to hold great promise for reducing fertilizer needs, but AID is not working with this technology. Although AID agricultural professionals in the Development Support Bureau have tried to initiate mycorrhizal research, it has failed to place high enough on their priority list to warrant funding in each of the last two years. AID interest in biological technologies has expanded, but the Agency staff feels funds remain the limiting factor. They feel their involvement in biotechnology research might help speed transfer and implementation of its results.

Workshop participants encouraged AID to place agricultural scientists from nonconventional fields of study on AID peer review panels of field projects and research activities. Because AID seemed committed to conventional agriculture, some workshop participants believed that AID needs fresh ideas to help their agricultural professionals move away from conventional paths and into new areas having potential for high payoff for LDCs. AID's peer review was likened to "an old boy system," one in which acceptance of new ideas was slow. Non-AID members also viewed the U.S. Department of Agriculture (USDA) dimly in the field of innovative biological research because they felt that USDA, too, primarily is committed to conventionality. Some participants thought USDA was not helping AID with the question of how to maintain productive soils in LDCs while reducing the input of expensive commercial fertilizers.

In the view of "agroecosystem" proponents, AID and some international agricultural centers place the greater part of their efforts on a few traditional food crops but do little to develop underexploited, nutritionally important new food crops. AID was viewed as having no interest in these "odd-ball" crops even though such foods contribute significantly to LDC diets. Proponents of the "agroecosystem approach" proposed looking into any food crops that fit into the local ecological system. Therefore, the resulting mix of crops might be radically different from the crop mix recommended by the "production approach," but one that could be sustained with lower fertilizer inputs.

An agroforestry system might be instituted that would integrate, for example, tree crops for food, fodder, firewood, and erosion control; native food crops; microbiological systems such as mycorrhiza and rhizobium; and local mineral resources such as zeolites into a low-energy consuming system. Participants encouraged AID to set aside a certain percentage of its appropriations each year to look for new, low-energy agricultural systems. The Agency could continue to back its efforts in "bread and butter" crops—corn, rice, etc.— but should be willing to commit some of its resources to nonconventional approaches. All participants agreed that AID should be encouraged to take some risks and not merely to back "winner" crops.

The Need for Flexibility

Most non-AID participants, as well as some AID staff, believed that the Agency needs a more flexible mechanism to provide funding for small-scale innovative activities. Currently, AID seems unable to transfer small amounts of money quickly or easily for such projects or experimental activities. The Agency claims that processing a small amount of money is as time-consuming as processing large grants or projects. Pressure within AID to obligate program dollars rapidly makes dealing with small projects bothersome. AID's agricultural professionals in the Development Support Bureau, for example, may wish to support certain inexpensive innovative activities, but they are discouraged by internal AID procedures and the program office's strong control. Consequently, scientists outside of AID who have special useful knowledge and who wish to participate in solving LDC agricultural problems feel that AID is neither open nor interested in outside assistance. Yet most participants felt that many aspects of both the "conventional production approach" and "agroecosystem approach" could be integrated with positive results.

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The non-AID scientists elaborated on how it is generally difficult for them to obtain needed support for innovative approaches to low-energy agricultural systems. The picture was similar for the varied researchers. First, there seems to be little support for funding the broad range of innovative biological technologies that may help improve LDC agricultural systems. This is particularly true at most U.S. universities because the universities find it difficult to support international activities that seem remote. Then, too, researchers who rely on the university for their salary commonly do not want to jeopardize their security by conducting nonmainline research.

Some of the non-AID researchers admitted that to carry out their chosen areas of LDC-related research they sometimes resort to using small amounts of money from other projects that are not LDC-related ("bootlegging"). Other common small funding sources for LDC-related research include a variety of Federal agencies other than AID, although AID does provide significant support for the biological nitrogen fixation work at the University of Hawaii. An AID grant provides partial support for azolla/algae research. Because Federal support for LDC-related research has the habit of vanishing suddenly, non-AID researchers face constant doubt about the continuity of their funding. The National Science Foundation, some United Nations institutions, small university grants, and private industry and institutions sometimes are funding sources as well. Private industry support seemed lacking for applied research in these fields.

The Need for Trained Aid Staff

Underlying all of the above problems was the strong need for a significant increase in the number of technically trained professionals in agriculture and natural resource areas in AID and its Missions overseas. Existing technical professionals need to spend increased time on the substance of their projects and less dealing with bureaucratic constraints. Without such an environment, AID may find it increasingly difficult to maintain or expand technical competence within its Washington offices or Missions in LDCs. A need for improved communication between scientists and the Congress was restated several times during the workshop, and activities similar to this workshop were cited as a step in the right direction.

PERCEIVED CONSTRAINTS

AID's major efforts in innovative agricultural research are directed primarily to the 13 international agricultural research centers to which AID contributes financial support. Much of the AID activity, however, depends on the work of the AID Missions and the ability of the professional staff to relate to the scientific community at large and to the Missions and regional or geographic bureaus. A number of problems in these areas were identified by the workshop participants.

Mission Agricultural Activities

AID Missions largely are removed from current science and technology developments in the academic and private sectors. Consequently, AID faces a difficult task in channeling new science and technology to field activities in most LDCs. In addition, AID staff at the workshop explained that many Missions feel that adequate technology already exists and that new science and technology are not needed. The Missions want AID technical people to solve the problems that the Missions identify using established technologies. This approach frustrates AID professional staff, including staff in the Agriculture Office.

CGIAR

AID considers its contribution to the Consultative Group on International Agricultural Research (CGIAR) valuable and feels that the

nonbureaucratic institution functions very well in addressing agricultural development problems and in implementing research results. AID sees Korea as a model of successful development where effective technology transfer has occurred, and feels that the Korea example should be used as a model for development activities by other LDCs.

Agricultural Staff

AID agricultural professionals attempt to maintain close contact with agricultural experts in the scientific community both within and outside of USDA. But the number of agricultural scientists in AID is so small that maintaining regular contact with their scientific colleagues can be difficult. AID employs about 4,000 people yet its Development Support Bureau (DSB), the bureau that provides technical support to all of AID's regional or geographic bureaus, has only 25 agricultural professionals. These 25 people managed about $70 million in agricultural projects in FY '80. Further, only about 10 percent of AID Mission personnel worldwide are agricultural officers even though some 50 percent of AID's development programs are agriculturally oriented. Because AID commonly reassigns its agricultural professionals to new Missions or back to the U.S. about every three to four years, many agricultural programs suffer from the lack of continuity. AID's workshop participants felt personnel rotations occur too frequently.

AID workshop participants felt that the Agency's emphasis on natural resource management should be increased but that this area is not receiving much Agency attention. Natural resource management requires an interdisciplinary approach, but because AID is segmented into numerous administrative compartments it is extremely difficult to conduct interdisciplinary activities. For example, agroforestry activities were to be transferred recently to DSB's Office of Forestry, Environment, and Natural Resources, the successor to the Office of Science and Technology (OST). Agroforestry, by definition, combines aspects both of agriculture and forestry, yet in the new arrangement, agroforestry is separated from agriculture.

The mandate to identify and test innovative and/or emerging science and technology and to transfer promising ideas to AID's Missions and Regional Bureaus belonged to the disbanded Office of Science and Technology. This office served as AID's "window" to the science and technology community and gave AID the opportunity to tap a broad array of innovative science and technology to help solve LDC problems.[2]

A problem that AID workshop participants highlighted repeatedly was that of the expanded role of AID program officers in decisionmaking and priority-setting for agriculture projects and research. Program officers commonly are generalists having little or no technical agricultural training. Organizationally, they sit between top bureau administrators and agriculturalists and other professionals and exert a strong influence on AID's agricultural efforts. AID agricultural professionals feel that they are continually second-guessed by program office generalists and that the technical content of proposed agricultural projects and research many times is adversely affected by the actions of the program office.

Program officers commonly evaluate project or research activities. But AID's evaluation process seems to foster a strong desire to have evaluations that show positive results. Without positive evaluations, the difficulty of moving subsequent projects through the AID system and, therefore, through the program office may increase. This perception, whether true or not, discourages some technical professionals from pursuing innovative opportunities because the element of risk in innovative activities generally is higher than in traditional approaches. The overall effect of having an inordinately strong program office is that agricultural professionals introduce fewer innovative technologies into AID agricultural programs.

[2]As of May 1981, a new Bureau for Science and Technology was formed. (See section on AID organization changes.)

Fall 1984 Addendum

Demand for the original House Foreign Affairs Committee publication on innovative biological technologies was high in the United States as well as many other countries and by 1984 copies were no longer available. Continuing requests for the publication have prompted OTA to reprint the document in its workshop series. Described below are some relevant policy changes that have occurred at AID since the 1980 workshop.

The atmosphere at AID today is more favorable toward new biological technologies. The current administration has expanded work on tissue culture and sees potential in other related areas. The attitude toward innovative crops, however, remains essentially unchanged and few resources are directed toward new crop development.

In its overseas Missions and within AID-Washington, there is still a scarcity of professional agriculturalists. Those that are on staff have many, diverse responsibilities so that innovative biological technologies do not receive much attention. Nevertheless, the National Academy of Sciences Board on Science and Technology for International Development (BOSTID) receives AID funds to seek new biological opportunities for developing countries. Since the 1980 workshop, research received increased attention in AID, however, the substantial budget cuts recently proposed in 1985 may adversely affect this trend.

One problem identified at the 1980 workshop concerned AID's inability to support small scale activities. AID appears to have improved some in this area. A new small grants program—the Program in Science and Technology Cooperation (PSTC)—has been established in the Office of the Science Advisor. The program is designed to stimulate new outside research on problems that confront developing nations. Priority funding is directed to five areas: Biotechnology/Immunology, Plant Biotechnology, Chemistry for World Food Needs, Biomass Resources and Conversion Technology, and Biological Control of Disease. This type of competitive, small grants program is an important step toward providing a more flexible mechanism to support innovative and small-scale research and technology development.

SUMMARY OF WORKSHOP SUGGESTIONS

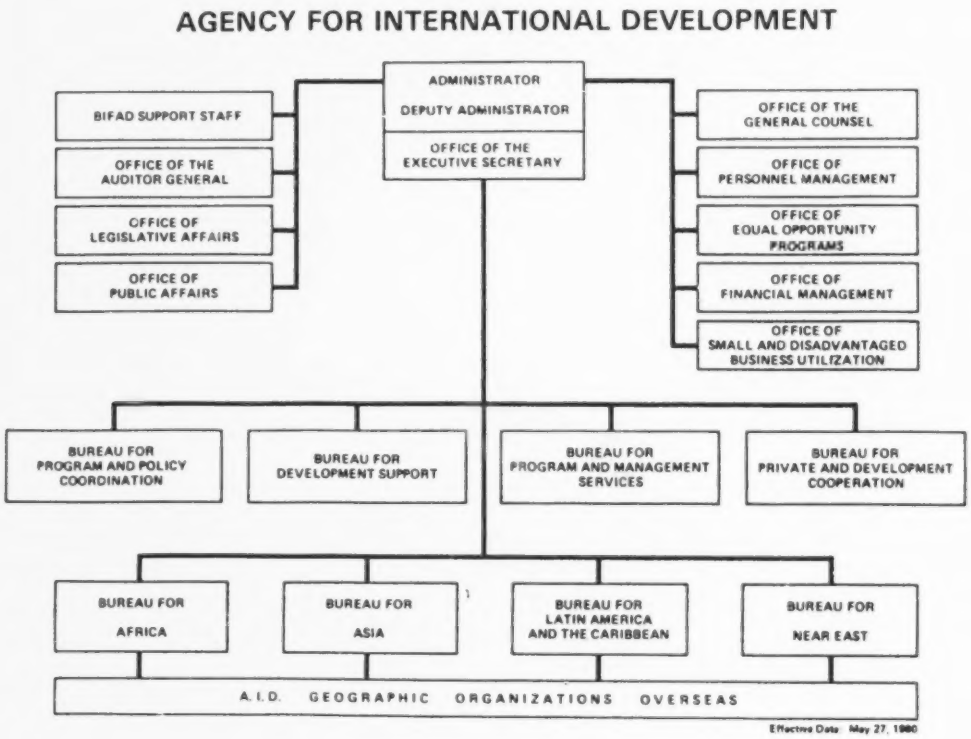
Summarized below are a variety of suggestions generated by the 40 participants during the course of the workshop discussions. Some of these topics received considerable attention and others much less. The participants were encouraged to express their points of view freely on any issues they felt were relevant. By doing so, the participants touched upon a variety of topics, many of which deserved more detailed examination than could be accomplished in two days. The issues that surfaced, however, should help the House Committee on Foreign Affairs in their oversight responsibilities of the Agency for International Development and in determining the role that innovative biolcgical technologies could play in enhancing soil fertility, improving food production, and reducing the need for expensive commercial fertilizers throughout the world.

* AID should greatly increase the number of in-house agricultural professionals in Washington and in the missions, especially in decisionmaking positions.
* AID should increase the number of Mission directors who are agricultural professionals. Similarly, effort should be made to encourage the selection of an increased number of people with professional agricultural training as ambassadors for LDCs.
* AID should encourage the U.S. and LDC private sector to participate in pilot-scale projects testing and developing innovative biological technologies.

* AID should appoint some outside experts in nonconventional agricultural technologies to its advisory committees and to its peer review panels.
* AID should broaden its inventory of scientists who might help AID expand its efforts into nonconventional agricultural practices.
* AID should streamline its procedures to encourage increased outside participation by U.S. scientists and technologies in small-scale innovative agricultural activities.
* AID should set aside a certain percentage of each agricultural project to integrate some new, innovative biological technology into the project.
* AID should fund some small-scale, pilot-type projects on the kinds of innovative biological technologies presented at this workshop and encourage the participation of outside scientists to work on the project as members of interdisciplinary teams. The need for pilot testing of a wide variety of innovative biological technologies by AID was stressed heavily and the need for risk-taking was encouraged.
* AID should increase its activities in agroforestry systems. These activities should be expanded to include both humid tropical regions and arid/semiarid regions. Pilot testing of the arid/semiarid systems could be carried out in the Southwest United States and LDCs.
* An expanded inventory of innovative biological technologies that could help LDCs reduce their need for expensive commercial fertilizers should be prepared, and institutions and individuals who have the skills for these technologies could be identified.
* OTA could conduct a full assessment of a broad range of innovative biological technologies that could help LDCs reduce the need for their use of expensive commercial fertilizers.
* AID should emphasize the transfer of technical information to LDCs and to AID mission agriculturalists, particularly on innovative biological technologies that might help LDCs reduce their need for expensive commercial fertilizers.

AID ORGANIZATION CHANGES

The Administrator for the Agency for International Development (AID) on May 21, 1981, announced a reorganization for the structure of AID (see following chart). One major change was the formation of a new Bureau for Technology and Science to replace the old Bureau for Development Support. Structurally, this change gives greater prominence to the role of science and technology in AID than has existed previously. Unlike the other AID bureaus for Science and Technology. Unlike the other AID bureaus which are headed by Assistant Administrators, the Bureau for Science and Technology is headed by a Senior Assistant Administrator, thus giving added strength to science and technology in AID.


AGENCY FOR INTERNATIONAL DEVELOPMENT
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OFFICE OF PUBLIC AFFAIRS
OFFICE OF THE GENERAL COUNSEL
OFFICE OF PERSONNEL MANAGEMENT
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OFFICE OF FINANCIAL MANAGEMENT
OFFICE OF SMALL AND DISADVANTAGED BUSINESS UTILIZATION
BUREAU FOR PROGRAM AND POLICY COORDINATION
BUREAU FOR DEVELOPMENT SUPPORT
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Chapter III

Underexploited Plant and Animal Resources for Developing Country Agriculture

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fence, was a winged bean plant laden with pods."

" 'But that's just sequidillas,' they said, disappointment echoing in their voices. 'It's only a poor man's crop!' "

It is a universal phenomenon that certain plants are stigmatized by their humble associations. Scores of highly promising crop plants around the world receive no research funding, no recognition from the agricultural community; they are ostracized as "poor man's crops."

For information on a poor people's crop one has to turn, more often than not, to botanists and anthropologists; only they will have taken an interest in the plant. Often there has been no agricultural research on it at all—no varieties collected or compared, no germination or spacing trials, no yield determinations or even nutritional analyses. And yet the crop actually may be crucial to the lifestyle—even the survival—of millions of people.

Just 50 years ago, the soybean itself was a poor people's crop. In the United States, it was spurned by researchers for more than a century after Benjamin Franklin first introduced seeds from the Jardin des Plantes in Paris. To be a soybean advocate then was to risk being considered a crackpot. Early in this century, Americans still considered the soybean a second-rate crop fit only for export to "poor people" in the Far East. But then, in the 1920s, University of Illinois researchers established a comprehensive soybean research program that helped sweep aside this discrimination. The soybean acquired new status as a "legitimate" research target, and its development gained so much momentum that it is now the world's premier protein crop.

Nowhere is the neglect of poor people's crops greater than in the Tropics—the very area where food is most desperately needed. The wealth and variety of tropical plant species is staggering. Some of the Third World's best crops are waiting in the poor people's gardens, virtually ignored by science. Merely to have survived as useful crops, suggests that the plants are inherently superior. Moreover, they are already suited to the poor person's small plots and mixed farming, as well as to poor soils, and the diet and way of life of the family or village. Examples are the winged bean and amaranths.

Winged Bean

Perhaps no other crop offers such a variety of foods as the winged bean. Yet it, remains a little-known, poor person's crop, used extensively only in New Guinea and Southeast Asia.

A bushy pillar of greenery with viny shoots, blue or purple flowers, and heart-shaped leaves, the winged bean resembles a runner-bean plant. It forms succulent green pods, as long as a man's forearm in some varieties. The pods, oblong in cross-section, are green, purple, or red and have four flanges or "wings" along the edges. When picked young, the green pods are a chewy and slightly sweet vegetable. Raw or boiled briefly, they make a crisp and snappy delicacy. Pods are produced over several months and a crop can be collected every two days, providing a continuous supply of fresh green vegetables.

If left on the vine the pods harden, but the pea-like seeds inside swell and ripen. When mature, the seeds are brown, black, or mottled. In composition they are essentially identical to soybeans, containing 34 to 42 percent protein and 17 to 20 percent of a polyunsaturated oil. The protein is high in the nutritionally critical amino acid lysine.

In addition to the pods and seeds, the winged bean's leaves and shoots make good spinach-like potherbs. Its flowers, when cooked, are a delicacy with a texture and taste reminiscent of mushrooms.

But perhaps the most startling feature of the plant is that, below ground, it produces fleshy, edible tuberous roots. These are firm, fiberless, ivory-white inside and have a delicious and delicate nutty flavor. The winged bean is therefore something like a combination of soybean and potato plants. And winged bean tubers are uniquely rich in protein—some contain more than four times the protein of potato.

Amaranths

Amaranths—major grain crops in the tropical highlands of the Americas at the time of the Spanish Conquest. They were staples of both Aztec and Inca. But the conquistadores banned the cultivation of amaranths because the grain was a vital part of native religion and culture. With this political move the Spanish struck a blow for their church but they also crushed the crop. For 500 years little has been done to study or promote it.

Amaranths belong to a small group of plants, termed C_4, whose photosynthesis is exceptionally efficient. The sunlight they capture is used more effectively than in most plants and amaranths grow fast. Vigorous and tough, amaranths have been termed self-reliant plants that require very little of a gardener. They germinate and adapt well to the rural farmer's small plots and mixed cropping. Furthermore, they are relatively easy to harvest by hand and to cook.

Amaranths are annuals that reach six feet in height and have large leaves tinged with magenta. They are cereal-like plants producing full, fat, seed heads, reminiscent of sorghum. The seeds are small but occur in prodigious quantities. Their carbohydrate content is comparable to that of the true cereals, but in protein and fat amaranths are superior to the cereals.

When heated, amaranth grains burst and taste like popcorn. In many regions, however, the grains are more often parched and milled. Amaranth flour is high in gluten and has excellent baking qualities; bread made from it rises and has a delicate nutty flavor.

Recently, W. J. S. Downton, an Australian researcher, has found that the grain of at least one amaranth (Amaranthus caudatus var. *edulis*) is rich in protein and exceptionally rich in lysine, one of the critical amino acids usually deficient in plant protein. Indeed, the amount of lysine exceeds that found in milk or in the high-lysine corn now under development.

Conclusion

It is very hard to get grants for research on poor person's plants. Funding agencies resist; the plants are unknown to most of them, and the literature to support any claims may be sparse.

Nonetheless, it is now time for agricultural research facilities throughout the world to incorporate poor person's crops into their research efforts. Third World agricultural development needs this balance, for only when his own crops are improved will the poor man be able to feed his family adequately. In future decades it may be—as in the case of the soybean—that today's poor person's plants will be feeding the world.

TREE LEGUMES: SHOCK TROOPS FOR THE WAR ON DEFORESTATION

Man has deforested one-third of South America's native forests, one-half of Africa's, and two-thirds of Southeast Asia's. It is critically urgent that the remaining forest cover be protected from indiscriminate harvest and that many now-deforested regions be reforested. A "thin green line" of fast-growing leguminous trees may be either our last line of defense or our first line of attack.

To most people legumes are limited to the dining table, but to plant scientists legumes include not only vegetables but shrubs, vines, and thousands of tree species, most of them indigenous to the Tropics. Actually, the family Leguminosae is the third largest in the plant kingdom. But out of the 18,000 different species of legumes, farmers extensively cultivate only about 20 species including peas, beans, soybeans, peanuts, clover, alfalfa, and even licorice. Foresters cultivate almost none.

The potential of tree legumes as useful plantation species remains largely unrecognized, yet they offer a particularly promising area for exploration in these days of devastating defor-

estation. Indeed, they seem to have special attributes that could put them in the front lines of the battle to reclothe the scarred hillsides throughout the Tropics.

Legumes, for example, are nature's pioneers in plant succession. They are among the first plants to colonize bare land. It therefore seems ecologically wise for man to deliberately exploit them for the same purpose: to quickly revegetate eroding or weed-smothered terrain, to halt erosion, and to provide protective ground cover under which slow-growing, climax-forest species can regenerate. Furthermore, many wood requirements might be met by these quick-growing small trees and they could help spare the last remnants of the natural forests.

Many woody legumes have a hardy, irrepressible character, suited to a wide range of soils, climates, altitudes, and environments. Like other pioneer species, they have a precocious nature and grow quickly in an attempt to overtop and preempt the space of their plant competitors.

Because of this innate competitiveness, many tree legumes are easy to establish and cultivate. Some can be direct-seeded (avoiding the expense of nurseries and transplanting fragile seedlings), and in some tests even spraying their seed out of aircraft has proven a suitable way to establish plantations. Many occur naturally in dense, pure stands, suggesting that they probably can be grown in monoculture without being decimated by pests.

A most important feature of many legume species is that nodules on their roots contain bacteria, which chemically convert nitrogen gas from the air into soluble compounds that the plant can absorb and use. Thus, for average growth these species require little or no additional nitrogenous fertilizer. Some produce such a surfeit of nitrogen—largely in the form of protein in their foliage—that they make excellent forage crops and the soil around them becomes nitrogen rich through the decay of fallen foliage.

To give an idea of the potential of this class of trees, three species of fast-growing legumes are mentioned below. Not one of these trees is widely exploited so far.

Leucaena

In the 1960s, University of Hawaii professor James Brewbaker found in the hinterland of Mexico certain varieties of *Leucaena leucocephala* that grow into tall trees. This was unexpected because the plant was previously known only as a weedy bush. In tropical climates, Brewbaker's varieties have grown so tall and fast that they can be twice the height of a man in just six months; as high as a three-story building in two years; and as tall as a six-story building with a trunk cross-section as large as a frying pan in only six or eight years.

In the Philippines, one hectare of these tall leucaenas has annually produced over 10 times the amount of wood per acre that a well-managed pine plantation produces in the United States. Even among the world's champion fast-growing trees, this is exceptional.

Leucaena wood is thin barked and light colored. For such a fast-growing species, it is remarkably dense (comparable to oak, ash, or birch), strong, and attractive. Its fiber is acceptable for paper-making and the wood can be pulped satisfactorily and in high yield.

But leucaena, a multipurpose plant *par excellence,* also has other uses. It can supply forage, for example, and researchers in Hawaii and tropical Australia have found that cattle feeding on leucaena foliage may show weight gains comparable to those of cattle feeding on the best pastures. Leucaena wood also makes excellent firewood and charcoal. Further, the plant is a living fertilizer factory for if its nitrogen-rich foliage is harvested and placed around nearby crops they can respond with yield increased approaching those effected by commercial fertilizer.

Although arboreal leucaena varieties have been cultivated for only a decade or so, they

are already being planted over tens of thousands of hectares in the Philippines. The World Bank has funded one large program. Batangas Province has a nursery producing 10,000 leucaena seedlings daily. The province's dynamic governor, Antonio E. Leviste, has decreed that other nurseries be set up throughout his province: in churchyards, cemeteries, schoolgrounds, roadsides—any idle ground. No government employee gets a paycheck until he has set up a leucaena plantation with at least 20 trees to produce seed. The consequent greening of Batangas has made citizens keenly appreciative of deforestation's ugliness and problems, as well as reforestation's rewards. Tree planting now interests the Batangas public intensely—not entirely for the sake of revegetating eroding watersheds, but for the income and benefits from exploiting leucaena forage, fuelwood, and "green manure." That the program has been adopted with gusto by the citizenry demonstrates the relevance of tree legumes to tropical problems as a sort of "appropriate forestry."

In more remote southern islands of the Philippines, leucaena (Filipinos call it ipil-ipil) is being planted over huge areas of former green-deserts, wastelands lost to coarse, sharp-edged "cutting-grasses." With its vigor and persistence, leucaena—if given a little care—can overtop the grasses, shading them out of existence, and converting waste ground to productive forest. It is essentially a permanent forest because after felling, the stump of a leucaena tree regrows with such vigor that the plant is said to literally "defy the woodcutter."

Calliandra Calothyrsus

In 1936, horticulturists transported seed of this small Central American tree to Indonesia. They were interested in it as an ornamental, for like other *Calliandra* species, it has flowers that are gorgeous crimson powder-puffs, glowing in the sunlight like red fireballs. But Indonesians instead took up *Calliandra calothyrus* as a firewood crop. Indeed, for 15 years steadily expanding fuelwood plantations of it have been established until they now cover over 75,000 acres in Java.

This small tree—barely taller than a bush—grows with almost incredible speed. After just one year it can be harvested. The cut stump resprouts readily giving new stems that can be 10 feet tall within six months. Some trees in Indonesia that are 15 years old have been harvested 15 times!

Calliandra wood is too small for lumber, but it is dense, burns well, and is ideally sized for domestic cooking. It is also useful for kilns making bricks, tiles, or lime and for fueling copra and tobacco dryers.

Indonesian villagers now cultivate *Calliandra calothyrus* widely on their own land, often intercropping it with food crops. The plant's value is dramatically exemplified by the village of Toyomarto in East Java. There, land that was once grossly denuded and erosion-pocked is now covered with calliandra forest and is fertile once more. Today the villagers actually earn more from selling calliandra firewood than from their food crops.

Conclusion

These are brief descriptions of only two species of small leguminous trees that have recently proven useful in combating deforestation in Southeast Asia. There are many other exciting species. In South Korea, foresters intercrop bushy *Lespedeza* species to provide firewood during the early years of the establishment of pine and other forests. In Central America, there are *Enterolobium cyclocarpum* and *Schizolobium parahyba,* in South America, *Mimosa scabrella (M. bracatinga), Schizolobium amazonicum,* Tipuana tipu, and *Clitoria racemosa*; and in the Pacific Islands, *Albizia minahassae* and *Archidendron oblongum.* In Africa, several fast-growing *Albizia (A. adianthifolia,* and *A. zygia,* for example) are indigenous, and two legume trees introduced from India, *Acrocarpus fraxinifolius* and *Dalbergia sissoo,* have shown exceptional growth rates on appropriate sites. In Asia, there are also *Acacia auriculiformis* and *Sesbonia grandiflora.*

In foresters' terms many of these species have "poor form." Their trunks may be too nar-

row or too crooked for construction timber or veneer. But, these are species for "peoples' forestry." Their role is for:

- farms, backyards, pasture lands, roadsides, canal banks and fencelines;
- village woodlots and energy plantations to fuel kilns, electricity generators, cooking stoves, and crop dryers;
- agrisilviculture (agroforestry), because they provide a wealth of products including forage, green manure, and food;
- use in shifting cultivation, because the natural drop of protein-rich leaves, pods, and twigs contributes nitrogen organic matter and minerals to upper soil layers and can markedly speed up the rebuilding of worn out soils;
- quick-rotation cash crops, both for the private landowner and the government forest department; and
- utility purposes such as beautification, shade, and shelter belts.

ANIMALS

When early farmers discovered that animals could be tamed and managed, they eagerly experimented with many of the species surrounding them. In Asia and the Americas, the silkworm, yak, camel, water buffalo, llama, alpaca, and guinea pig were selected. Egyptian tomb paintings at Saqqara painted in 2500 B.C. show addax, ibex, oryx, and gazelle wearing collars and obviously domesticated. Ancient Egyptians apparently domesticated hyenas and baboons, as well.

But then the process essentially stopped. Today's farmers raise the same animals their Neolithic forebears were familiar with more than 10,000 years ago. (One exception is the rabbit, which French monks tamed between the 6th and 10th centuries because the Church considered newborn rabbits to be fish and they could be eaten when the Church calendar demanded abstinence from meat.) Although the world's menagerie contains some 4,000 species of mammals alone, only a mere six domestic animals produce virtually all of the world's meat and milk.

As agricultural man spread himself about the globe, he dragged with him this handful of species. He carried them beyond their natural boundaries, forced them upon strange and often fragile environments—usually driving out the native species that previously predominated there, and often drastically changed the environments to accommodate them.

Very little meat is eaten in developing countries and because most of them are in the Tropics, it is not possible to change that much with cattle, sheep, and pigs. These animals have an evolutionary adaptation to the temperate environments from which they originated and are limited in their ability to adapt to new ones. But the world's fauna is a rich genetic bank that may be tapped to increase world food production. Some of the potential species are unexpected ones, as highlighted below.

Toads, Snails, and Guinea Pigs

In rural areas of developing countries, it is important to produce small animals. They fit better into village life and they can be eaten at one meal, so the lack of refrigeration is no hindrance. In Chile, there's a shiny, olive green toad (*Calyptocephalella caudiverbera*). It is a giant toad that can weigh three pounds or more. Its meat tastes like a cross between lobster and chicken. It grows to be a foot long or more and lacks the toxic skin glands and warty appearance of other toads. Because of its superb and enigmatic taste, the wild toad has long been a delicacy of Chilean gourmets. But now, researchers at the La Serena campus of the University of Chile are learning how to farm them.

In 1975, the University's Institute of Food Technology started farms large enough to pro-

duce 100,000 of the choice toads every two years. The intensive methods they developed have made it feasible to supply 10 to 15 tons of scallop-sized toad legs each year to grocery stores, restaurants, and canneries.

The Institute also has dug production ponds out of otherwise useless swampland. The eggs, larvae, tadpoles and adults are all kept apart because the voracious toads have no hesitations about cannibalism. Normally, however, they feed on small fish, crabs, crawfish, and aquatic plants. The ponds are surrounded with flowers and shrubs to attract insects and boxes of rotten fruit are placed nearby to draw fruit flies to the area. With their long sticky tongues, the toads eagerly capture the insects. Other than this, the toads reportedly are given little attention and in two years they reach market size: about 7 inches long and weighing one-half pound.

Researchers are ecstatic over the ease and cheapness of toad farming, and they are looking toward the lucrative international frog meat market to export the tender, white drumsticks of these unique Chilean toads.

In Nigeria, the Institute of Oil Palm Research is developing another potentially valuable new resource: the giant African Land snail (Achatina species). This snail grows rapidly and may weigh up to half a pound. It is eaten widely in West Africa and is immensely popular in parts of Nigeria and Ghana. The meat has as much protein as beef, but it has considerably more of the important amino acids, lysine, and arginine, than even eggs contain. The Institute has found the snails suitable for "farming" in shaded enclosures under the trees in rubber, cocoa, or oil-palm plantations. With proper proportions of males and females, it has produced as much as 150 pounds of snail meat in the small enclosures each year.

In Peru, scientists are looking to their indigenous fauna too. One of Peru's serious and permanent problems is a lack of beef. Two-thirds of the steaks of which Peruvians are so fond are imported despite the nation's chronic dollar shortage. The situation became so serious that five years ago the military junta put a ban on beef consumption 15 days in every month. Chicken production was once believed to be the answer to the problem, but although it has grown fast, so has the population. Big hopes were placed on fish, too, but the country lacks the financial resources to install the facilities needed for national marketing. The guinea pig is now believed to be the best answer so far to the problem posed by the short supply of animal proteins.

Guinea pig is a traditional staple. Although domesticated in the time of the Inca, it has not previously attracted much research attention. Yet guinea pig is widely consumed in Peru. The nutritional value of its meat compares favorably with that of other meats. The animals can be raised in urban areas and in villages, where larger animals are scarce or impossible to keep. The fast growth and rapid reproduction makes the guinea pig a sensible resource in the Peruvian environment. Added to this is the fact that guinea pigs can live off vegetation that is of inadequate nutritive value for feeding other livestock.

These resources are strange—even repugnant—to the majority of specialists working to increase food production and improve human nutrition in developing countries. But to the local inhabitants they are traditional foods that are much sought and enjoyed.

Crocodiles

In Africa, South and Southeast Asia, Australia, and South America, the populations of crocodiles, alligators, and caimans are fast headed for extinction. In Papua New Guinea (P.N.G.) in the 1960s, the two native crocodile species were headed the same way. But not today. In the last five years, a remarkably innovative project in this, one of the newest and most underdeveloped nations, has caused a dramatic turnaround in the crocodile's drastic decline there. Though the P.N.G. story has not been told widely, it is one with immense implications for the survival of crocodilians elsewhere. It is also a demonstration of how resources can be managed to conserve a species, to minimize impact on a fragile environ-

ment, and to provide wealth in remote villages in a developing country.

The P.N.G. program is based on an appreciation for crocodile biology. Each year, a female may lay between 30 and 70 eggs. Although most of them hatch, predators so relish the tender and remarkably vulnerable young hatchlings that almost none survived the 15 years needed to reach breeding size. In nature, then, there can at any time be found a plethora of tiny crocodiles, but a paucity of breeders. Commercial hunting worsens the imbalance because hunters always seek the biggest specimens, regardless of the resulting damage to the breeding populations.

Recognizing that a ban on hunting would be largely unenforceable in remote areas (and grossly unpopular where man-eaters sometimes occur), the P.N.G. Government decided in 1970 to restructure the trade so that shooting breeders would lose its attraction and the profit would come from exploiting the hordes of tiny hatchlings that would result. This was done through a law banning the sale of large skins, supplemented by a stiff tariff on small skins.

Today, villagers in the steamy swamps of P.N.G. have tens of thousands of tiny crocodiles in their care. They raise them for a year or two and can sell them for up to $100 each. Crocodile farming has already become the main cash earner for the people there. I personally met a village leader in Wewak who had come to oversee shipment of $14,000 worth of skins headed to New York by airfreight.

The P.N.G. crocodile project is characterized by:

- *Good Science*: Despite popular "man-eater" impression, crocodiles live mainly on fish, though the researchers in P.N.G. have found that young ones also grow well on frogs, snails, and beetles. The feeding efficiency is astounding: One and one-half pounds of food gives one pound of weight gain, and foot-long animals can grow to be five and six feet long in less than two years. (Conventional domestic livestock require five to eight pounds of food to produce one pound of weight gain.) Crocodile farming is also space efficient: dozens of animals are raised in an area the size of a household living room; in a swamp or jungle, that's important.
- *Good Conservation*: Because the program is based on harvesting young hatchlings from the wild, the economic value of the wild populations and their habitats becomes forcefully apparent. The program's future depends on them. It gives economic value to wildlife protection. Out of pure self-interest, the people become guardians and conservers of habitats and wildlife. In a sense, the farming project is just a tool for conserving the species in its own wild habitat.
- *Good Sociology*: The villagers have a sophisticated knowledge of the crocodile; the animal is part of their culture and heritage. They don't have to be taught how or where to catch crocodiles, and they take quickly to the program. Introducing cattle or Western-style crop-raising would require massive and tedious education and training.
- *Good Environmental Management*: The program is based on living with the existing landscape and resources. It requires none of the bush-clearing fencing, forage-grass planting, or pesticide spraying that rearing other domestic animals would demand. That's important in a fragile tropical rainforest ecosystem.
- *Good Economic Development*: What other agricultural product could give a $14,000 income in a remote jungle village?

Butterflies

In remote jungle towns in the north of Papua New Guinea are operating butterfly farms—some of the most unusual farms in the world. Around the edge of a field, flowering shrubs are planted to attract the adult butterflies whose mouthparts are adapted for drinking nectar from flowers. These butterfly "forages" include hibiscus, flame-of-the-forest, and the strange, pipe-like aristolochia. Within half-acre circlets of these flowers are planted leafy plants

that the caterpillars feed on. The combination provides a complete habitat where butterflies find everything they need for their life cycle. Thus few leave, and the farmer retains his livestock without fencing or walls.

Butterflies may seem exotic livestock to us, but even in the remotest P.N.G. jungle, a villager knows and understands their habits, location, and lifestyle. And butterflies don't require bank loans, veterinary services, artificial insemination, or the other impediments of conventional livestock. Also, when farming insects, the villager can work when and if he wants to: there are no deadlines. No hard labor and no danger, either. To a Papua Guinean, the strange thing is that people are willing to pay for a butterfly.

And pay well they do. Ounce for ounce, exotic butterflies are far more valuable than cattle. And worldwide demand for butterflies is rising. Millions are caught each year and sold to museums, entomologists, private collectors, and perhaps most of all, to ordinary citizens. The fragile, iridescent creatures, mounted in plastic, decorate purses, trays, tabletops, screens, and other ornamental objects.

With their butterfly farms many rural Papua New Guineans are for the first time participating in a cash economy and butterflies are beginning to improve the welfare of many villages. At Bulolo, the government has established an insect-buying agency to help the butterfly farmers of Papua New Guinea. It purchases insects from farmers and fills specific orders requested by overseas buyers. Profits go to the villager.

Perhaps the most striking feature of the program is that it is actually conserving, and even increasing, the numbers of butterflies. Basically, it is an exciting, pioneering conservation project because it develops a tremendous economic incentive to preserve populations and habitats—the program relies on healthy wild populations to keep the farms stocked.

Because of this, conservation organizations are becoming excited by the program, seeing in it a model that could be duplicated to help save endangered exotic butterflies everywhere.

FUEL

The fuels paradise of recent decades has blinded us to the possibilities of alternative energies, especially those for powering vehicles. The internal combustion engine, however, remains the most immediately practical prime mover for motor transport. Finding alternative energy sources for it poses one of the most severe problems facing the world. The world is not so much running out of energy as it is running out of liquid and gaseous fuels. Living plants that produce liquid fuels would indeed be boons for the future. Farmers would become energy producers. Today this is already a distantly glimpsed possibility. Two examples are given below.

The Gasoline Plants

Near Irvine in southern California can be found a field of what is perhaps the most revolutionary and little-explored development in modern agriculture. The crop is *Euphorbia lathyris* and this field is the first attempt at cultivating this wild cactus-like shrub. It is the brainchild of Melvin Calvin, professor of chemistry at the University of California at Berkeley. *Euphorbia lathyris* and related species produce a milky latex, one-third of which is composed of hydrocarbons—compounds similar to those found in crude petroleum oil. Although there are as yet few hard facts on which to base firm projections, Calvin estimates that the plants might be capable of each year producing 10 to 50 barrels of oil per acre.

The hydrocarbon in *Euphorbia lathyris* and similar species is principally polyisoprene, the same molecule that makes up rubber in the rubber tree. But in *Euphorbia,* it is liquid rather than solid. This is because it is a smaller mol-

ecule, but Calvin points out that its hydrocarbon molecules are similar in size to those found in crude oil. He thinks that *Euphorbia* type hydrocarbons might even be processed into fuels and petrochemicals in existing oil refineries.

A distinguished scientist, Calvin received the 1961 Nobel Prize for Chemistry in recognition of his achievements in unraveling the chemical processes of photosynthesis. Growing petroleum plants is a new venture for him, but already he projects that this country's vast petroleum demands could be met by plantations covering an area the size of the State of Arizona. He calculates the costs of harvesting petroleum from trees to be competitive with current oil prices: a total of between $5 and $15 per barrel for growing and processing the plants.

A plantation of such plants should be economic in dry lands unsuitable for growing food. Though little is known of their requirements or yields, *Euphorbia* species are hardy and need little or no irrigation and care. Calvin foresees that the plants will be mowed near the ground and the harvested plants crushed to release latex in much the same fashion as is done with sugar cane. The stumps quickly resprout new stems so that replanting would be unnecessary.

This is truly a pioneering concept, and the field near Irvine is the first small step in evaluating its practicality. Already, larger plantations are planned. The University of Arizona has a million-dollar grant from the Diamond Shamrock Corporation to develop *Euphorbia lathyris* into a crop; the Government of Kenya is investing (perhaps unwisely) $10 million in plantations. If such projects are successful, this obscure wild plant will enable the world's desert countries to have oil fields on top of the ground.

Diesel Fuel You Grow on the Farm

Ohio State University (OSU) in Columbus, Ohio, transports students around its spread-out campus using a fleet of buses. Nothing unusual in that. But, this year (1980) OSU is using soybean oil as fuel.

Over the past decade, various student projects at the OSU engineering school have shown that vegetable oils can be used as fuel for diesel engines. For a full year the university has run a large, 60-passenger bus partly on soybean oil. The experiment proved so successful that in September the whole university fleet was switched to the new fuel.

The soybean oil is collected from deep-fat fryers in cafeterias and kitchens across the University, filtered through muslin cloth by the engineering students to remove gunk and solids, and blended into diesel fuel. A ratio of one part soybean oil to four parts diesel was settled on as it gave a stable mixture, lowest fuel consumption, and actually smoked less than diesel fuel alone.

The first bus maintained its normal 40 hour a week schedule. After 4,500 miles on the soy-diesel blend the engine was taken apart and inspected. Little or no abnormal wear had occurred. The engine was actually in such fine shape that it was merely reassembled and returned to service without further attention.

Although it is little-known to the general populace that diesel engines can be run on vegetable oils, this knowledge is not new. In the 1890s, Rudolf Diesel concluded that any material that was injectable and would ignite at the temperatures generated by compressing air could serve as fuel for his engine.

During World War II this knowledge was put to use. When Japan was cut off from petroleum supplies, the 65,000 ton *Yamoto,* the largest and most powerful battleship of its time, used edible, refined soybean oil as bunker fuel. Japanese forces occupying the Philippines and Allied troops trapped in northern Burma used coconut oil for fueling diesel trucks and generators.

Since then, that experience has been largely forgotten. But in the U.S., South Africa, Australia, Brazil, Canada, Thailand, Japan, and perhaps elsewhere, individual researchers are rediscovering that diesel tractors, buses, and

stationary engines can operate when fueled with sunflower, soybean, peanut, rapeseed, and other vegetable oils.

The experiences are usually solitary and most involve only very short running times. The practical potential of vegetable oils as commercial diesel fuel substitutes is therefore uncertain. But, at least in the short run, they work.

Of all the research laboratories testing diesel engines fueled by vegetable oils, the South African government's Division of Agricultural Engineering has the most experience. At its laboratory near Johannesburg it is running 10 tractors on sunflower oil. Fiat, International Harvester, John Deere, Landini, Massey Ferguson, and Ford tractors are being used. With two exceptions the tractors started satisfactorily on undiluted sunflower oil. All operated normally, delivered almost full power, and had virtually the same fuel consumption as on diesel fuel. A Ford 7000 tractor has run trouble-free for almost 1,400 hours of operation on a farm using a blend of 20 percent sunflower oil and 80 percent diesel fuel. At the end of this time it was found that deposits in the combustion chamber, cylinders, and piston ring grooves were no worse than those formed burning normal operation on diesel fuel. On the other hand, carbon deposits on the injector nozzles were worse and contributed to an eventual 4 percent power loss and serious gumming of the crankcase oil.

The rapid compression of fuel and air in the cylinder of diesel engines generates enough heat to ignite the mixture and power the engine. Unlike a gasoline engine, no spark is needed. Injecting the fuel into the combustion chamber is the most crucial step in a diesel engine. The fuel must be forced in against the pressure of the compressed air and to make this doubly difficult, the fuel has to be in the form of mist. If not atomized, the fuel burns slowly and unevenly, reducing engine efficiency, raising unburned pollutants in the exhaust and the lubricating system, and even forming deposits of solid carbon in the engine itself.

Vegetable oils are more viscous and less easily atomized than diesel fuel and are therefore more difficult to inject successfully. This is probably why the injector tips suffered build-ups of carbon. Coking and the resulting incomplete combustion diluted the lubricating oil and gummed it up because vegetable oils will polymerize when they are hot and next to metal.

The South African engineers, however, have found a way that seems to avoid these difficulties. They slightly modify the sunflower oil in chemical reactions using small amounts of ethanol or methanol. The resulting ethyl or methyl esters derived from sunflower oil caused much less coking than diesel fuel itself. Furthermore, they produced much less exhaust smoke, and the engine ran quieter so that the characteristic diesel knock was less audible. And, against all expectations, the engine gave more power with the new fuel than with diesel fuel. Thus tractors were running on a renewable fuel grown by farmers and achieving better results than on diesel fuel. Much yet remains to be done to test the widespread applicability of these results, but it is a line of research that is bright with promise.

CONCLUSION

Development specialists usually promote resources and technologies that are familiar to their own lives. Most agronomists, foresters, animal scientists, and nutritionists know little about the wealth of plants and animals to be found in the developing world. They all but ignore the significance poor people's crops, leguminous trees, and animal resources such as snails, guinea pigs, and butterflies. Instead they recommend and sponsor the introduction of species that are foreign and unconnected to the lives of those they want to help.

This paper identifies just a few exciting underexploited resources for developing country agriculture. Detailed information on them and

many others can be found in the following National Academy of Sciences reports (all of which are available without charge from the Commission on International Relations, JH 215, National Academy of Sciences, 2101 Constitution Avenue, N.W., Washington, D.C. 20418):

- *The Winged Bean: A High Protein Crop for the Tropics*
- *Leucaena: Promising Forage and Tree Crop for the Tropics Underexploited Tropical Plants With Promising Economic Value*
- *Tropical Legumes: Resources for the Future*
- *Guayule: An Alternative Source of Natural Rubber*
- *Making Aquatic Weeds Useful: Some Perspectives for Developing Countries*
- *Firewood Crops: Bush and Tree Species for Energy Production*

Chapter IV

Native Plants: An Innovative Biological Technology

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Contents

	Page
Abstract	51
Introduction	51
The Role of Native Plants in Sustaining Food and Forage Production	52
Where Native Plants Are Being Used Today	53
Research Efforts on Native Plants	56
How Do/Could Native Plants Increase or Decrease the Need for Fertilizer, Pesticides, Irrigation, and Machinery?	58
Fertilizer	58
Pesticides	59
Irrigation	59
Machinery	60
What Is the Potential Role of Native Plants to Restore, Improve, or Sustain Food Production on Tropical and Subtropical Soils?	60
What Research, Development, and Implementation Scenarios Could Help Native Plants Realize Their Potential of Enhancing Tropical Soil Productivity?	61
Scenario A	61
Scenario B	61
Scenario C	61
What Changes in Attitude Are Needed?	62
Cultivators	62
Legislators	62
Financiers	62
International	62
What Biophysical, Cultural, and Socioeconomic Conditions Would Be Conducive to Project Implementation?	62
Biophysical Conditions	63
Cultural Conditions	63
Socioeconomic Conditions	63
What Are the Major Constraints on Development and Implementation of Native Plant Use?	63
Scientific Constraints	63
Environmental Constraints	64
Culture Constraints	64
Economic Constraints	64
Political Constraints	64
How Would Implementation of a Native Plant Technology Affect the Need for Capital?	65
What Would Be the Impact of Wide-Scale Implementation of Native Plant Use on Socioeconomic Structure?	65
References	66

Table

Table No.	*Page*
1. Little Used But Potentially Useful Plants	54

Chapter IV

Native Plants: An Innovative Biological Technology

ABSTRACT

The concept of native plants reflects a new direction in botanical development. The term implies the idea that rather than adapting the environment to the plant, an indigenous plant expresses the best adaptation to an environment and improving on this expression will yield various benefits. Bringing marginal lands into widespread agricultural use often employs technologies and plant species inappropriate to these situations. This occurs with a total disregard for the climatic limitations of the environments. A new approach is required.

Development of native or indigenous plants, particularly those adapted to tropical and subtropical soils, could be beneficial at different economies of scale. In some instances, their development will be small and amenable to use by individual farmers or farming groups. On the other hand, there will be instances where development will be large scale and have international implications.

Native plants can be particularly useful in sustaining fertility on depleted or marginal soils and improving general productivity. They use an "agroecosystem approach" to obtain necessary production. Polycultural (mixed) cropping systems are especially applicable in tropical locations; they rely heavily on the potential of adapted or indigenous plants. Native plants represent an underused resource and constitute an opportunity for positive botanical developments.

The coordinated, integrated development of indigenous plants could allow for multiple and additional benefits greater than the initial goals of soil fertility, food production, or raw materials. There is an immediate need for inventories of existing native crops for their development potential. The world's tropical and subtropical germplasm is poorly known. Throughout the world, knowledge of plants and their uses by indigenous peoples is disappearing because farming systems are being converted to monocultural uses. Germplasm storage of potentially valuable varieties and strains requires immediate attention. Demonstration of practical working models with specific native plants must be performed.

One factor limiting the development of native or other unconventional plants is an institutional bias against them. The major emphasis of plant research during the last 100 years has been directed at the dozen or so primary food crops—to the exclusion of almost everything else.

To overcome this institutional bias will require innovation in policy, research and development, and program implementation. Development of native or adapted plants should allow for an integration of these concerns. The capabilities of various governmental and nongovernmental institutions should be directed toward the goal of sustaining soil productivity in both the short- and long-term context.

INTRODUCTION

The purpose of this paper is to present a nontechnical description and evaluation on the utility of "native" plants as an innovative technology to improve productivity on soils in tropical/subtropical areas. The paper addresses several major questions that appear as subsections.

The term *native plant* needs clarification. All plants may be considered native or indigenous to some location on the earth, but when a plant is taken to an area where it is not naturally found, it becomes an introduced species. This distinction is too constraining and can overlook the importance of adaptation—judged either from actual observation or from scientific evidence of ecological similarity. In this report, native species are those plant species growing in an area that have not been exploited for commercial development and export. Some native species may have desirable attributes and a potential for intensive use while others may merely serve to "fill in the spaces" of the plant community and have only minor development potential. This paper is limited to indigenous species that have not been extensively developed.

Native plants hold great promise for meeting the expanding needs of society for food, fiber, fuel, and enhanced land productivity. In the search for a plant or plant product to serve a market or domestic need, plants native to a given region may already express the range of adaptation necessary for sustained use. But they are often overlooked in favor of an imported species. A good example of indigenous plants being overlooked is in rangeland improvement programs in the Western United States where native shrubs were removed in order to plant introduced grasses (11). Although plant exploration and introduction has been emphasized by the economically developed nations, the search for new plant materials has been directed along conventional lines and the potential of native species has been overlooked.

In the past, the common procedure has been to examine existing files or materials found in plant introduction stations to find new plants and plant products rather than to explore locally for possible new products. Because of the increase in energy costs and the energy component in existing production activities, a new look for alternatives is justified. A particularly attractive opportunity to develop native plants exist in tropical and subtropical areas. These areas generally have not been of interest as a source of plant materials because the developed nations are, to a large extent, located in temperate climates. This has limited germplasm collection, research testing, and introduction of new crop species. Additionally, most American primary crop species are introductions from the Old World, and these have been genetically developed over long periods of time for intensive agricultural use.

THE ROLE OF NATIVE PLANTS IN SUSTAINING FOOD AND FORAGE PRODUCTION

Native plants serve a traditional role in many tropical and subtropical countries. Various indigenous species have been used for food, fuel, livestock feed, construction, fiber, medicines, and other purposes on a sustained yield basis. The species are either gathered from natural plant communities (forests, rangelands, marshes, etc.) or harvested from small farmed plots under various degrees of cultivation. Cultures as diverse as Mexico, Sri Lanka, and Indonesia have well-documented histories of wide use of indigenous plants for medicines, foods, and other uses. Most of these native plants have not reached a level of development sufficient to make them commercially useful. Notable exceptions include rubber, corn, pineapple, and potatoes. Most species, however, are unspectacular in their attributes and find beneficial use only in the day-to-day existence of the local people.

Overuse of native species brought about by population increases and energy shortages is creating adverse impacts on many species and their systems of production. Where previously a conservative level of plant use generally assured their natural replacement and did not reduce their genetic diversity, exploitation of

land resources by overgrazing, intensive agricultural development, forest clearing, industrial development, and widespread soil degradation threatens to eliminate many useful species.

For example, a recent National Academy of Science assessment of environmental degradation of the groundnut basin of Senegal (12) indicates that overuse due to population increase and cyclic drought has resulted in the disappearance of many native species used for fruit and livestock fodder. Theoretically, some of these species are still present in the noncultivated bush areas. An example is *Ziziphus maritiana*, a desirable fodder shrub, that had essentially been eliminated from areas adjacent to intensively cultivated farmlands by overuse. At a conference in Australia on Genetic Resources of the World, concern was expressed that valuable genotypes and gene combinations were being lost due to the impacts of human population expansion. Associated with the direct loss of genetic resources is a substantial reduction in soil fertility and an increase in less desirable plants.

Native plants also play an especially important role in improving crop performance and diversity. Indigenous or locally cultivated relatives of many common crop plants offer significant potentials for crop improvement programs within the temperate and tropical latitudes. Recent discoveries of wild perennial relatives of corn (*Zia mays*) could prove extremely important to the future development of this crop. Similarly, the expression of expanded environmental adaption often inherent in many native plants could allow for much wider cultivation of the species while reducing artificial inputs. Recent work with salt tolerance in major grain crops and tomatoes relies heavily on the adaptive qualities of various native and overlooked indigenous relatives of these important crops (13).

WHERE NATIVE PLANTS ARE BEING USED TODAY

Native plants are being used all over the world. Many species find extensive use in developed agriculture and some native species already enjoy limited commercial use in areas of optimum adaptation (table 1). *Opuntia* cactus fruits in central Mexico are collected and sold locally. Fibers are removed from the *Leghugea* cactus for use in making Mexican mats, shoes, and baskets. Numerous species of native trees such as Mangosteen (*Garcinia mangostana*) in southeast Asia, Naranjilla (*Solanum quitoense*) in Colombia and Ecuador, pejibaye peach palm (*Guiliema gasipaes*) in Central America, and soursop (*Annona muricata*) of the West Indies produce exotic fruits for local markets.

The important point is that the usefulness of some species is known only to local people or is generally not appreciated by a wide audience. A number of examples of fruit, vegetable, fiber, oil, and forage species are described by the National Academy of Sciences in their studies on underexploited plants (18). Such underdeveloped species may possess unique features that could be useful in new applications or supplement existing crop plants if they were screened for optimum size, shape, product quality, and adaptability to various management practices.

The genus *Atriplex* is an example of a group of semiarid, subtropical plants currently used but possessing significant potential for increasing rangeland productivity. Various shrubby *Atriplex* species are valuable as livestock forage during seasonal dry periods when most grasses are below required levels of crude protein for animal nutrition. The protein content in *Atriplex* is high and balanced. The exploitive subsistence level grazing practices and extensive gathering of *Atriplex* on the rangelands of Syria, Iraq, and other Middle Eastern nations has nearly caused the disappearance of these palatable shrubs (23). An integrated development program of collection and revegetation with this native species and other adapted

Table 1.—Little Used But Potentially Useful Plants

Common Name	Scientific Name	Useful Portion	Potential Use	Present Growing Areas	State of Cultivation	Present Yield Per Hectare Per Year	Time to First Harvest
A. Humid Tropics							
Cocoyam	*Xanthosoma sagittifolium*	tuber	carbohydrate, protein	Tropical Americas, West Africa	domesticated	30–60 tons wet weight	3–10 months
Peach palm or pejibaye	*Guilielma gastpaes*	fruit and stem	carbohydrate, oil, protein, "heart of palm"	Central and Northern South America	domesticated	3 tons	6–8 years
Taro and dasheen	*Colocasia esculenta*	tuber	carbohydrate	Egypt, Philippines, Hawaii, Caribbean	domesticated	22–30 tons wet weight	6–18 months
Buriti palm	*Mauritia flexuosa*	fruit kernel, shoots, trunk and leaves	oil, starch, vitamins A and C, timber, cork, fiber, "heart of palm"	Amazon Basin, Venezuela, Guianas	mostly wild	?	?
Babassu palm	*Orbignya martiana*	fruit and kernel	oil, protein, fuel	Amazon Basin	mostly wild	1.5 tons	10–15 years
Pequi tree	*Caryocar brasiliensis*	fruit and kernel	oil, fuel	Amazon Basin, Central Brazil, Guianas	mostly wild	?	9 years
Seje palm	*Jessenia polycarpa*	fruit	oil resembling olive oil	Amazon Basin	wild	22 kg/tree per year	?
Winged bean	*Psophocarpus tetragonolobus*	pods, beans, tubers, foliage	protein, oil, carbohydrate, livestock feed	Papua New Guinea, Southeast Asia, Sri Lanka	domesticated	2.5 tons of dry beans	10 weeks
Durian tree	*Durio zibethinus*	fruit	carbohydrate, fat; vitamins, flavor	Southeast Asia	haphazardly cultivated	?	7 years
Mangosteen tree	*Garcinia mangostana*	fruit	highly prized flavor	Southeast Asia	domesticated	50 kg/tree per year	15 years
Pummelo tree	*Citrus grandis*	fruit	large citrus fruit	Southeast Asia	domesticated	?	several years
Soursop tree	*Annona muricata*	fruit	fruit and juice	Southern China, Australia, Africa, tropical Africa, West Indies	domesticated	6–10 tons	?
Uvilla tree	*Pourouma cecropiaefolia*	fruit	grapelike fruit	Western Amazon	wild	?	3 years
Chaya bush	*Cnidoscolus chayamansa*	leaves	vitamin-rich leafy vegetable	Mexico and Central America	domesticated	?	2–3 months
Ramie herb	*Boehmeria nivea*	stems and foliage	fiber and livestock feed	East and Southeast Asia, Brazil	domesticated	1.4 tons fiber, 20 tons feed	2 months
Cauassu herb	*Calathea lutea*	leaves	commercial wax	Amazon Basin, Central America	wild	0.8 tons of wax	9 months
Leucaena	*Leucaena leucocephala*	leaves, wood, pods, seeds, bark	livestock feed, timber, fuel, paper, soil fertilizer, dye stuffs, human food, erosion and watershed control, nurse tree, fire and wind breaks	Central America, Mexico, Southeast Asia, Northern South America, Australia, Hawaii, East and West Africa, Papua New Guinea, Caribbean, India	domesticated and wild	12–20 tons of forage, 20–50 tons of wood	less than 1 year to more than 3 years, depends on variety planted
B. Semiarid and Arid Tropics and Subtropics							
Channel millet	*Echinochloa turnerana*	seed, leaves, and stems	carbohydrate, protein, livestock feed	Central Australia	wild	?	several months after heavy rain
Buffalo gourd	*Cucurbita foetidissima*	seed, root	oil, protein, starch	Mexico, Southwestern United States	mostly wild	2.5 tons of seed, 22 tons starch	2 years
Guar (cluster bean)	*Cyamopsis tetragonoloba*	seed, leaves, and stem	gum, protein, oil, livestock feed	United States, Pakistan, India, Australia, Brazil, South Africa	domesticated	18–24 tons green fodder, 0.9–2 tons seed	3–5 months

Table 1.—Little Used But Potentially Useful Plants—Continued

Common Name	Scientific Name	Useful Portion	Potential Use	Present Growing Areas	State of Cultivation	Present Yield Per Hectare Per Year	Time to First Harvest
Apple-ring acacia tree	*Acacia albida*	leaves, shoots, pods, seeds	livestock feed, human protein	Tropical and Southern Africa	wild	200 kg protein	several years
Ramon tree	*Brosimum alicastrum*	leaves, twigs, nuts	livestock feed, carbohydrate, protein	Central America, Southern Mexico, Caribbean Islands	mostly wild	?	several years
Cassia shrub	*Cassia sturtii*	leaves	livestock feed	Australia, Israel	wild and cultivated	1/2 ton dry weight	1–1.5 years
Saltbush shrub	*Atriplex* spp.	leaves and shoots	livestock feed	worldwide in warm arid zones	wild and cultivated	1–1.5 tons	2 or 3 years
Candelilla shrub	*Euphorbia antisyphilitica*	stems and leaves	hard wax	United States and Mexican deserts	wild	?	2–5 years
Tamarugo tree	*Prosopis tamarugo*	pods and leaves	high protein, livestock feed	Atacoma desert of Chile, Canary Islands	cultivated	10–20 sheep	5 years
Jojoba shrub	*Simmondsia chinensis*	seeds	liquid wax identical to sperm oil	United States and Mexican deserts, Israel	mostly wild	2 tons	3–5 years
Guayule shrub	*Parthenium argentatum*	whole plant	natural rubber	United States, Mexican deserts, Spain, Turkey	mostly wild	0.33 ton	1 year
C. Mountain Environments of Low Latitudes							
Grain amaranth	*Amaranthus caudatus*, etc.	seed, leaves	high lysine, high protein, starch, vitamins	Andean region of South America	domesticated	higher than maize	several months
Quinoa (grain)	*Chenopodium quinoa*	seed	protein, carbohydrate	Andean region of South America	domesticated	?	5–6 months
Peruvian parsnip	*Arracacia xanthorrhiza*	tubers, stems, leaves	carbohydrate, livestock feed	Andean region of South America	domesticated	?	10–14 months
Naranjilla shrub	*Solanum quitoense*	fruit	fruit and juice	Central and Northern South America	domesticated	1–2 tons of fruit	6–12 months
Winged bean	*Psophocarpus tetragonolobus*	pods, beans, tubers, foliage	protein, oil, carbohydrate, livestock feed	Papua New Guinea, Southeast Asia, Sri Lanka	domesticated	2.5 tons of dry beans	10 weeks
D. Saline Environments							
Eelgrass	*Zostera marina*	seed	carbohydrates, protein	tidal flats and estuaries in all latitudes	wild	?	?
Pummelo tree	*Citrus grandis*	fruit	citrus fruit	brackish marshy areas in Thailand	domesticated	?	several years
Saltbush	*Atriplex* spp.	leaves and shoots	high protein, livestock feed	worldwide, including salty soils and saline irrigation waters	mostly wild	1–1.5 tons	2 or 3 years
Tamarugo tree	*Prosopis tamarugo*	pods and leaves	high protein, livestock feed	Atacama desert of Chile, Canary Islands	cultivated	10–20 sheep	5 years
Salt grass	*Paspalum vaginata*	leaves and stems	livestock feed, sand stabilization	seacoasts from Australia to Spain, Argentina to Baja California	mostly wild	?	1 or 2 years
Spirulina, blue-green algae	*Spiruline platensis* *Spiruline maxima*	entire alga	poultry feed, very high protein human food	Lake Chad, Valley of Mexico	cultivated	3 tons protein	several days

Atriplex species from similar climates could substantially restore rangeland productivity to this region.

Another example of a native plant that is receiving considerable attention on a pilot-scale level is jojoba (*Simmondsia chinensis*), an evergreen shrub indigenous to the Sonoran deserts of the United States and Mexico. The plant is valued for the liquid wax contained in its seeds. The wax is similar to sperm whale oil and has a potential for use in many industrial processes. Field test plantings have been made in Arizona, California, Israel, Mexico, and Australia. Because the plant is adapted to areas of extremely low rainfall (less than 10 inches), it could become an important cash crop for the appropriate arid areas (10).

RESEARCH EFFORTS ON NATIVE PLANTS

Research on native plants is being conducted by many different groups ranging from private individuals and companies to State, national, and international agencies. However, no coordinated research effort can be expected because of the diversity of potentially useful native species, the various countries where they are growing and could be grown, and the risks involved in developing new crops for ill-defined markets.

As has probably been the case throughout history, plant resources have been developed to meet existing and short-term needs. The difference today is the high cost of bringing new products into a highly competitive market. Opportunities for new products or uses from native plants can occur as a result of changes (or potential for changes) in consumer preferences or as existing products come into short supply and can be replaced by a native plant product.

It is difficult to identify organizations performing research on native plants, but they fall into the following categories:

1. Broad spectrum agencies sponsoring exploration collection and evaluation. Examples:
   - USDA: plant introduction, plant materials centers (nationwide).
   - FAO (Food and Agriculture Organization of the United States) seed exchange, international development.
   - SIDA (Swedish International Development Agency): sponsoring projects to preserve genetic resources.
2. Agricultural experiment stations doing work on individual plant species with local concern. Examples:
   - University of California Agricultural Experiment station, Riverside: jojoba wax.
   - University of Hawaii Agricultural Experiment Station: Leucaena trees.
3. Private organizations, agricultural enterprises working to develop products from various species. Examples:
   - Firestone Rubber Company: guayule for rubber development.
   - Native Plants, Inc.: developing new technology for tissue culture propagation of various plants.
   - Jojoba International, Inc.: encouraging commercial plantings of jojoba.

Funding of native plant research is very dependent on the species in question. Obviously the potential for some species is greater than others depending on the scarcity and quality of the expected product, the abundance of the plants, and the needs of society. Currently, there is a high interest in native plants with potential as sources for biomass energy. Unfortunately, there is little, if any, coordination in research funding for native plant development or in the establishment of priorities. As of 1979, the total U.S. funding for research and development of underexploited plants was limited to less than $10 million, half devoted to jojoba.

The uncertain path of development for a natural rubber product from the native shrub

guayule (*Parthenium argentatum*) illustrates the problems of developing a native plant. The National Academy of Sciences (13) pointed out that in 1904 a company was formed to extract rubber from the guayule bush. By 1910 this company was the sixth largest in Mexico but the wild stands of plants quickly became depleted. Expelled from Mexico by Pancho Villa, the company continued limited operations in Salinas, California. Cut off from natural rubber supplies from Southwest Asia in 1942, the United States took over the company and planted over 12,000 hectares of production and experimental plots of guayule. These fields were just coming into production after the war in 1945, but because natural rubber was again plentiful and a fledgling synthetic rubber industry gained the Federal price supports, the guayule fields were destroyed. Recognizing the need for dependable supply of natural rubber, Congress passed the Native Latex Commercialization Act of 1978 which makes $30 million in Federal funds available for research. Subsequently, Firestone Tire and Rubber Company and Goodyear Tire and Rubber Company have initiated field trials of guayule in the Southwest. In Mexico, plans are underway for a natural rubber industry using guayule from native stands and later from established plantations.

Obviously, a more integrated and organized effort will be needed to bring the benefits of other native plants into reality. The research community and society simply cannot be subjected to the vagaries of 70 years when a plant of national value takes so long to be developed. Coordination is needed to stimulate innovation in policy planning, research and development funding, and commercial implementation.

Substantial, integrated programs are necessary to bring native plants into commercial production. We know that genetic quality of conventional crops and appropriate cultural practices have been improved over a long period of time. With this history of development, we can expect that new crops/products from native plants can be developed with even greater efficiency. Significant breakthroughs may take place (such as the application of various biotechnologies) but for the most part, research funds, time, and vision will be needed to unlock these new resources.

One of the first research steps must be to identify promising native plants and describe some of their characteristics. A survey sponsored by the National Science Foundation (22) described six new crops with a potential for development in the United States. A thorough coverage was given to ten new agricultural crops (20) that already have received some attention. Goodin and Northington (8) helped stimulate interest in native plants with their conference on Arid Land Plant Resources.

Probably the greatest stimulus to the development and use of native plants in recent years has been the series of bulletins published by the National Academy of Sciences. *Underexploited Tropical Plants With Promising Economic Value*. NAS (18) describes 36 tropical and subtropical plants that have a high potential for use as cereal, root, vegetable, fruit, oilweed, forage, and fuel. *The Winged Bean—A High Protein Crop for the Tropics* (17) provides information on a tropical legume native to Southeast Asia and New Guinea with a potential for improving human nutrition. *Guayule: An Alternate Source of Natural Rubber* (14) is a report on the development potential of a subtropical desert shrub of Mexico and Southwestern United States that produces a latex product similar to natural rubber from Southeast Asia. *Leucaena: Promising Forage and Tree Crop for the Tropics* (15) provides information on a vigorously growing tree and bushy plant that produces nutritious forage as well as restoring soil fertility. Other benefits include timber, fuel, and pulpwood as well as soil conservation and stabilization. *Tropical Legumes, Resources for the Future* (13) reports the findings of a group of legume specialists on 200 species that warrant research and development to achieve their optimum potential. *Products From Jojoba* (16) gives a review of the chemistry of the liquid wax obtained from this shrub native to Southwestern U.S. deserts.

These publications all highlight the immense potential existing within the botanical world to benefit agriculture, forestry, and horticul-

ture, particularly in the developing countries. These and other surveys consistently document the immediate need to inventory indigenous knowledge concerning native plants and their uses, germplasm collection and storage, and conservation of existing habitats. The rapid disappearance of extensive semiarid, subtropical, or tropical plant community compounds the problem of collecting, researching, and developing these under-exploited plant resources.

HOW DO/COULD NATIVE PLANTS INCREASE OR DECREASE THE NEED FOR FERTILIZER, PESTICIDES, IRRIGATION, AND MACHINERY?

Any change in the present use pattern of fertilizer, pesticides, irrigation, and machinery would depend completely on the nature of the native plant being developed—whether the particular plant could be developed on an intensive or extensive basis, or the degree to which the plant is susceptible to insects and diseases. However, any move to increase productivity would generally require an increase in the level of inputs. The adaptation of some indigenous plants to multicropping systems or polycultures could significantly reduce the need for artificial inputs. The development of such production systems is just in its infancy, however, and models appropriate to widespread application are virtually nonexistent.

Some specific examples of inputs required by various native plants will illustrate their variable nature.

Fertilizer

Three possibilities for fertilizer use may be seen:

1. Legume species may have minimal fertilizer requirements, needing mainly phosphorus, sulfur, and micronutrients.
2. Some native species may not require high levels of fertilizer because of their adaptation to low nutrient environments.
3. Non-legume species may require substantial amounts of fertilizer to achieve optimal production levels.

Leguminous native plants are particularly attractive because they can serve to increase soil nitrogen as well as provide useful products such as fuel, forage, and wood biomass. Fast growing Leucaena trees have been shown to provide foliage containing 1,000 to 1,300 lbs. of nitrogen a year and can restore the fertility of tropical soils depleted of nitrogen and organic matter (15). Felker (15) suggested that mature tree legume orchards receiving no irrigation or nitrogen after establishment may increase soil fertility up to four times greater than non-leguminous tree species. Numerous legume shrubs and trees such as *Acacia, Prosopsis, Desmodium, Cassia,* and *Stylosanthes* enhance soil fertility while at the same time serving as live fences, crop interplantings, or range and pasture fodder. Many examples of soil fertility increase are presented in *Tropical Legumes: Resources for the Future* (13), *Tropical Pastures* (21), and in papers presented at the International Symposium on Browse in Africa.

Some native species may not require large amounts of fertilizer because they are adapted to soils of medium to low fertility. Under such conditions, plant growth and production could be expected to be correspondingly low. If high yields for commercial production are desired, the level of fertility must be increased accordingly. Intensive cropping has been shown to deplete soil fertility and any continuous production in a new agricultural location would eventually require regular soil fertilization.

Non-legume native plants may require large increments of fertilizer to produce at levels sufficient to be commercially attractive and to cover costs of production and development. These species are those requiring optimal soil and water conditions. Possible requirements for fertilizer and other inputs for such crops

are summarized in a report prepared for the National Science Foundation (22).

Another potential strategy is represented by the selection and development of native plants adapted to saline environments. The ability to tolerate environmental constraints and still produce utilitarian byproducts is one potential avenue for overcoming high fertilization inputs. This is an approach to native plant development that has been virtually ignored in plant research. The existence of salt tolerant wild selections of existing crops could improve the infertility tolerance of these species and therefore reduce their needs for fertilization. Such possibilities will require concerted efforts to enhance the range of adaptability for most crop species.

Pesticides

Very few, if any, of the native plants having a high potential for development have been studied from the aspect of insect, disease, or weed problems normally associated with intensive cultivation. Whereas many insect or disease organisms may be held in check in a diverse plant community, they may increase to epidemic proportions when their host plant is grown in a pure stand. An example of such an epidemic occurred when black grass bug populations nearly devastated pure stands of introduced wheatgrasses that had been seeded to replace sagebrush and other plants in western rangelands (9). Plantings of native species will require research and plant protection measures similar to those already necessary for the production of conventional crops.

In tropical countries where multicropping systems represent the most sustainable method of farming systems, the pesticide requirements could be minimized by host/predator interaction within the farm plots (7). Testing and development of such models needs to be greatly expanded, however.

Irrigation

Requirements for irrigation will depend on the kind of native plant selected. As a concept, the use of native plants indicates an adaptability to the specific environment and its constraints. Species adapted to tropical soils may not require irrigation if the pattern of rainfall is adequate and meets the critical stages of plant development. Areas of subtropical soils typically have periods of rainfall deficiency and various strategies must be employed to obtain production under such conditions. These strategies include:

1. Choose native plants with low water requirements that can be grown in desert or semi-desert conditions. Some examples are: jojoba, atriplex, guayule, buffalo gourd, guar, cassia, acadia species (19).
2. Develop technologies to increase the effectiveness of natural precipitation or irrigation. Alternate fallow, spaced plantings, water harvesting, or drip irrigation can be effective. Where land is not a limiting factor, these extensive practices can be economically effective. Evanari, et al. (4), demonstrated how an ancient civilization survived in the Negev desert by using precipitation optimizing practices such as water harvesting and spaced plantings. Recent work at the University of Arizona (6) indicates high potential for using water harvesting to foster plant production under desert conditions. Biomass plantings, deep rooted tree crops, and drought adapted species would be most suitable for these technologies.
3. Use available irrigation water to support maximum production of new crops from high yielding native plants. Where soils with a high productive potential may be available for intensive use, possibly by replacing a lower value traditional crop with a high value new crop, irrigation may

be justified. Close plantings, tillage, pest control, and fertilization may also be needed to optimize production. Grain amaranth, winged bean, and guar are possible species for intensive development, but many other may be considered.

Machinery

Because of the varied nature of native species available for development, no definite statement can be made regarding machinery requirements. Equipment for land preparation, tillage, and transportation of crops to storage and market would be needed. Harvesting may be done by machinery in the case of a uniform plant such as guar or guayule where leaves and seeds are easily available. Where fruits, stems, or roots are not uniformly exposed and are retained on the plant, either hand labor or a specialized piece of machinery may be needed.

In regions of the world where hand labor is abundant for planting, cultivating, and harvesting, the development of new native crops that require hand labor rather than machinery is most appropriate. In other nations, labor intensifying machinery can be developed. This has been the pattern followed in the development of conventional crops.

It is important to recognize that the development of native plants for their various uses can be aimed at local needs as well as at wider industrial and international markets. Machinery and labor requirements will depend on what level of development is pursued.

WHAT IS THE POTENTIAL ROLE OF NATIVE PLANTS TO RESTORE, IMPROVE, OR SUSTAIN FOOD PRODUCTION ON TROPICAL AND SUBTROPICAL SOILS?

There is a high potential for some native plants to positively affect food production on tropical and subtropical soils. One of the most promising strategies is the increased use of leguminous plants as food, livestock fodder, and wood to concurrently improve soil fertility (21). As fertilizer costs continue to escalate in response to energy expenses, fertilizers will become economically prohibitive in many developing countries. Incorporation in the cropping system of a legume rotation, green manure, or animal manures derived from legume feeds may be the best remaining option to replace fertilizers (12) and maintain agricultural productivity.

Non-legume native species have various potentials for positive benefits to food production. Many species are already known locally but have not received sufficient notice to be introduced or developed for use in other (similar) regions. To achieve such recognition will require:

1. A shortage in food from existing crop plants.
2. Development of new lands that are better suited for new crops.
3. Adaptation of new crops to compete economically with conventional crops.

Some form of research and development intervention will be needed to raise the perspective and incentives of local peoples. The likelihood of general use depends on the individual species. For example, the general qualities of seeds from the jojoba plant have been known for many years (10) but only recently has any development effort appeared substantial enough to bring the plant into widespread use.

The shortage and cost of sperm whale oil is a big factor motivating jojoba development in more than five countries. Some applications will be less spectacular, but no less needed. Plantings of the legume tree *Acacia albida* in Mali (24) hold considerable promise for im-

proving subsistence agricultural production there, but the effort is but a "drop in the bucket" compared with the needs in that area of West Africa.

In view of the diversity of native plants available for development and the number of countries with suitable environments, judicious support of native plant development programs seem justified. The likelihood of spontaneous development or widespread use of native plant resources seems unlikely without external encouragement. Otherwise, many useful native plant species and ecotypes stand in jeopardy of being lost as deforestation, land depletion, industrial development, or other activities eliminates the natural plant communities.

WHAT RESEARCH, DEVELOPMENT, AND IMPLEMENTATION SCENARIOS COULD HELP NATIVE PLANTS REALIZE THEIR POTENTIAL OF ENHANCING TROPICAL SOIL PRODUCTIVITY?

Scenario A

The program of planting seedlings of *Acacia albida* legume trees in Mali (24) serves as a model for the development of the potential of a native plant. In this program, CARE set up production nurseries to produce tree seedlings in soil-filled plastic tubes. *Acacia albida* is an indigenous legume tree native to sub-Saharan Africa. The tree has the unique feature of being leafless during the rainy season. This allows for cultivation of other crops directly under the tree. The leaves and pods provide fodder and green manure and the roots fix nitrogen. It is an ideal candidate for selection, improvement, and application to various semiarid agroforestry systems.

Teams of local farmers were employed to plant the seedlings in preselected agricultural/pasture areas of good soils. Planters were paid on a per tree basis for planting and protection. Subsequently, these local people were encouraged (in their work training orientation) to take a special interest in the seedlings to see that they received appropriate management and protection to ensure their survival from grazing animals. Benefits expected are increases in soil productivity and livestock feed.

Scenario B

A scenario for planting a living fence of a legume shrub to enhance soil fertility by N-fixation and livestock manure might be as follows. Seedlings could be propagated at a government research station after selection from depleted stands of palatable shrubs. These plants would then be distributed to village elders for allocation to heads of families for planting around the fields and houses in the immediate vicinity of the village. This would enhance kitchen garden production and feed small livestock through the dry season. Excess fodder could be used on the farm plots as green manure.

Scenario C

A scenario to develop a high value, native tree, fruit crop would logically start with a program of selecting the most desirable biotypes for their fruit quality, tree size and form, and maturity pattern. Because of the long-term requirements for genetic improvements that would combine the best qualities in various selections, a dual development program would be undertaken. The first would be to vegetatively propagate (by rooted cuttings of a few plants or by tissue culture for thousands) the best selection(s). Propagules would normally be grown in containers until ready for field transplanting. Sufficient acreage would be planted to provide experience in intensive management and production for a local, regional (city), or international cash market. As experience is gained with product acceptance, the criteria for the genetic breeding program

would be modified. By the time suitable genetic materials would be available, the market requirements would be sufficiently known to guide large-scale development plantings and improved cultural practices, possibly involving machinery.

Levels of capital and manpower needed could be determined or extrapolated on the basis of experience with a pilot program. Pilot demonstration programs are a plausible way to approach development of the most promising native plants.

WHAT CHANGES IN ATTITUDE ARE NEEDED?

One of the most critical attitudinal problems in developing new crops from native plants is one of institutional interest in sustainable and diversified plant development. Traditional crops, mostly of temperate origin, have received the majority of institutional attention from government, research, and commercial organizations. A new and more innovative approach to plant development is required when referring to native or adapted plant development. The various groups that directly affect these development efforts include the following:

Cultivators

All efforts should include the local farmers. The objective would be to seek sufficient involvement on planning, planting, and management to bring local people to thinking that the project is theirs—not something imposed from outside by government. The active efforts of an individual farmer in the Dakotas to bring sunflower into widespread cultivation is an example of the importance of this element in the introduction of "new" crops.

Legislators

Politicians should be encouraged to provide a favorable and stable policy for product development, to be optimistic but not raise unrealistic expectations, and finally to be willing to support financial needs of the pilot project. The efforts of the Guayule Commission is an example of this coordinated effort at policy and implementation.

Financiers

Banks and bankers need to be educated about the realities and potentials for development of a new crop. Available capital for second phase development would be needed if the private sector is to follow the pilot development. Orientation and involvement would be needed to assure support when it is needed. Tax incentives and loan guarantees may be useful ways for financial institutions to foster more rapid development and diversification of new crops.

International

Policymakers within the international donor community need to understand the risks as well as the opportunities for a successful program. Stepwise project implementation is a desirable approach where needed research and development experience is gained as the program develops. This approach could be implemented directly by requiring agricultural, forestry, and horticultural development projects to direct a certain percentage of the program to native species or varieties. Means for involving host country politicians, research people, and local farmers are crucial.

WHAT BIOPHYSICAL, CULTURAL, AND SOCIOECONOMIC CONDITIONS WOULD BE CONDUCIVE TO PROJECT IMPLEMENTATION?

Obviously, the best place for a native plant development project would be where it is needed most. However, there are qualifications to this simplistic statement.

Biophysical Conditions

To be successful, a native species needs a high degree of adaptation to the climate, soils, topography, and animal uses, including resistance to parasites. From an ecological standpoint, the approach should be to seek areas that are ecologically equivalent to the original habitat of the native plant species. This is usually done by testing plantings in various locations of similar climate. However, the time period during which the plantings are under observation may not be sufficient to experience the range of environmental extremes that is common to the area. Detailed experiments under greenhouse and controlled environment chambers may help to document the full range of adaptation possessed by the species.

Cultural Conditions

For a new crop or agricultural product to be successfully produced, it must not be contrary to the cultural traditions of the people to grow, consume, or use. For example, an improved high protein maize (corn) variety was considered in India, where there were food shortages. However, the yellow color of the seed coat was objectional because it resembled a grain product fed to animals (1). A social custom study would be advisable to determine if any taboos, customs, or adverse values exist regarding the potential crop and its required production practices.

Socioeconomic Conditions

Critical to the development of any new crop from a native plant is whether the product is socially acceptable and whether local people can handle the costs of development. There is less chance of gaining social acceptance of a project if the payoff period is far into the future. An early return on the investment may be needed to maintain interest and commitment to a project. Further, the amount of capital required may exceed the capacity of individuals or banks to handle. Thus, smaller increments of development and interim returns to investment may be necessary. An example with animals should illustrate this point. A farmer could finance the purchase of several animals of an improved breed of goat or a pen of rabbits, but he may not be able to finance a cow or bull. There is also greater risk in having a high amount of capital tied up in one individual.

The above conditions are most likely to exist in the less developed tropical countries, in the more rural and remote regions of such a country, and with people of tribal or nomadic social organization. The less educated people would likely be more difficult to reach and less willing to accept a development program.

Communication tools such as radio, newspapers, and films could be used to help both in the search for useful plants as well as disseminate information on new uses and opportunities for economic diversification.

WHAT ARE THE MAJOR CONSTRAINTS ON DEVELOPMENT AND IMPLEMENTATION OF NATIVE PLANT USE?

Development of a native plant species to commercial or economically significant levels would not be easily accomplished based on current observations of jojoba and guayule. Many constraints must be overcome to satisfactorily develop the potential of a native plant.

Scientific Constraints

A major scientific problem in plant development is lack of technical information. A sufficient amount of general information is needed to identify plants of high potential. Additional

species information can help determine feasibility for development and the suitability of products or uses to meet identified needs. Progress toward development may well depend on technical data regarding planting, management, harvest, processing, and conservation. Pilot demonstration programs designed to answer technical problems are essential.

Particularly needed are scientific studies on ways to establish plants and obtain optimum productivity under arid, semiarid, and tropical conditions. Problems dealing with microorganisms and plant growth, drought resistance, physiology of stress, and application of engineering to improve adaptation present challenges for scientific research on indigenous plants.

Environmental Constraints

Existing land uses may pose one of the largest constraints to native plant development. But such commitments of land must be seen in relation to the long-term values. Where decreasing soil fertility and vegetation degradation are occurring, a shift to a leguminous native plant could bring multiple benefits. For native plants with industrial potential (i.e., guayule), processing may influence air and water quality. Whether costs can be internalized in the value of the product of plant use must be determined. In most instances, the environmental benefits of developing native or adapted plants will most likely outweigh the negative impacts. The potential to reduce existing environmental degradation and more sustained land use must be considered positive consequences.

Culture Constraints

Native plant development may cause social change, community growth, and increased need for services. Such changes need to be addressed, but at this time little information is available. In general, the cultural impacts from developing new crops or practices from native plants should be positive or neutral. In the context of tropical countries, the perceptions of regional, community, tribal, or family groups must be considered. Resistance to change may be manifested by refusal to cooperate or allow project development. Involvement of local leaders and decisionmakers is a necessity.

Economic Constraints

The major economic constraint to development is probably the lack of seed money, venture capital, or government support to conduct pilot-scale programs. From the pilot program, cost data can be extrapolated for planting, production, transportation, and marketing. From these preliminary data, decisions can be made toward major financing and long- or short-term commitment of funds, either by the private sector or through government grants and loans. Because of the generally speculative nature of developing high potential native plants to meet needs that are not clear, private sector funding may have to be government subsidized.

Political Constraints

A major political constraint is the instability and short longevity of many political leaders in less developed countries. Although a new crop development program may be highly favored by one political leadership, the prospect of change must be considered. Because agricultural development is highly important and not as politically sensitive as other sectors of a country, it should be possible to work within political constraints as long as the project does not appear to run counter to current political and social philosophy.

For example, pilot plantings of palatable fodder shrubs in Syrian rangelands by FAO and the Syrian Ministry of Agriculture were described as an extension of cooperative marketing and fattening units to increase meat production and increase the stability of the livestock industry (2). In reality, the system had many free enterprise profitmaking opportunities to increase the incentive of individuals to participate in the scheme. Yet political leaders touted the success of this cooperative project and declared it to be in harmony with the so-

cialistic philosophy mandated by the government. New crops must not appear to compete with existing production systems, but should complement them. Constituents must be convinced that the proposed developments will provide benefits equitably. Additionally, adapted crops that could represent a higher cash return than traditional crops should receive special attention from the international donor community.

HOW WOULD IMPLEMENTATION OF A NATIVE PLANT TECHNOLOGY AFFECT THE NEED FOR CAPITAL?

Because of the varied types of native plants, no specific capital requirements can be determined for all native plants. There is no doubt that a native plant development program would require significant inputs of technology and capital. However, those plants that produce a crop would require greater inputs than those used for reforestation, improving soil fertility, or increasing rangeland forage production.

Careful analysis of the infrastructure of a region or county may give an indication of available processing capacity. For example, vegetable oil extraction facilities are available in the groundnut basin of Senegal and might be available in the off-season to extract hydrocarbon latex from giant milkweed plants that grow in waste places and margins of fields. A small pilot program with these native plants could provide some of the data necessary to determine the feasibility of proceeding to larger phases of development. In a like manner, any proposed new crop should be analyzed for capital inputs and available facilities for production processing and transport.

WHAT WOULD BE THE IMPACT OF WIDE-SCALE IMPLEMENTATION OF NATIVE PLANT USE ON SOCIOECONOMIC STRUCTURE?

It would be false to assume that only a large commercial-type farm or a family-sized farm would be suitable for native plant development. Much depends on the nature of the plant species and the magnitude of development necessary. From table 1, it can be seen that some crops such as cocoyam and buffalo gourd could easily be grown on small plots and collected for commercial markets. In contrast, industrial feedstocks, biomass, and high volume crops such as guayule, ramie, leucaena, and guar would better be grown in large fields and be harvested and treated mechanically.

Small field operations would cause little change on socioeconomic structure except to provide an additional income stream to communities. Large operations may disrupt communities by increasing their population or requiring the establishment of new communities. An excellent example in the United States is the 110,000 acre Navajo Irrigation project near Farmington, New Mexico. This large commercial farm operation has left little opportunity for community development of a traditional native culture, nor has it provided an opportunity for family farm or cooperative group farm development. The project has addressed only the large-scale production-economic aspects of development. Socioeconomic problems remain unsolved as illustrated by the attempts being made to resettle Navajo workers in a modern subdivision quite foreign to existing patterns of community settlement.

In summary, the various options available in native plants of high potential for development could enhance existing social and economic patterns or could disrupt them with large developments depending on the suitability of the land, the adaptability of native plants to given locations, and the institutional insensitivity that might prevail in their development.

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Chapter V

Multiple Cropping Systems: A Basis for Developing an Alternative Agriculture

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Contents

	Page
Abstract	69
Introduction	69
Concepts and Definitions	70
The Basis of Multiple Cropping	71
Yield Advantages of Crop Mixtures	71
General Resource Use	73
Specific Resource Use, Conservation, and Management	75
Agroforestry: A Multiple Cropping System	79
Socioeconomic Implications of Multiple Cropping Systems: Perspectives for the Future	80
References	82

List of Tables

Table No.	*Page*
1. Definitions of the Principle Multiple Cropping Patterns	71
2. Related Terminology Used in Multiple Cropping Systems	71
3. Biological and Physical Factors: The Advantages and Disadvantages of Multiple Cropping Systems Compared to Sole-Cropping or Monoculture Systems	72
4. Social and Economic Factors: The Advantages and Disadvantages of Multiple Cropping Systems Compared to Sole-Cropping or Monoculture Systems	73
5. Yields of Corn, Beans, and Squash Planted in Polyculture as Compared to Low and High Densities of Each Crop in Monocultures	74
6. Effects of Mixed and Row Intercropping on Yields and Nutrient Uptake of Corn and Pigeon Peas in St. Augustine, Trinidad, Expressed as Relative Yield Totals	76
7. Biomass Distribution of Dry Matter in a Corn/Bean Polyculture as Compared to a Corn Monoculture, in Tacotalpa, Tabasco, Mexico	76
8. Classification and Examples of Agroforestry Technologies	80

Figure

Figure No.	*Page*
1. Distribution of the Relative Yield Totals of Mixtures Based on 572 Published Experiments	72

Chapter V

Multiple Cropping Systems: A Basis for Developing an Alternative Agriculture

ABSTRACT

This paper presents a general discussion of the concept of multiple cropping, including a description of the different types of systems, and the advantages and disadvantages of their widespread use, both biological and socio-economical. These systems are designed to intensify agricultural production both in terms of yields per unit area and through the more efficient use of space and time.

Examples of yield increases with multiple cropping systems are expressed in terms of Relative Yield Totals (RYT) or Land Equivalent Use (LER) where the production per unit area with the multiple crops is greater than the sum of equivalent areas planted to monocultures. This increase in production is explained by higher overall efficiency of resource use.

Specific examples of the effects of multiple cropping systems on resource use, conservation, and management are discussed. Variables considered include microclimate, light, soil, water, pests, diseases, weeds, crop interactions, space, and time. The special case of agroforestry, which combines trees with crops and grasses, is discussed.

In conclusion, the socioeconomic implications, both advantageous and disadvantageous, are discussed. Also, the great potential for multiple cropping systems in agriculture in the United States is presented. Research needs to be directed to test these alternatives.

INTRODUCTION

Multiple cropping is not a new form of agricultural technology, but instead is an ancient means of intensive farming. Multiple cropping has been practiced in many parts of the world as a way to maximize land productivity in a specific area in a growing season. Generally, the practice of planting two or more crops on the same field is more common in tropical regions where more rainfall, higher temperatures, and longer growing seasons are more favorable for continual crop production. As population has increased, increasing the need for agricultural production, the use of multiple cropping systems is more prevalent. Though the history of multiple cropping is old, the concept has received very little attention from agricultural scientists, and what limited interest exists has come about very recently.

Why was this interest increased so dramatically in such a short time? Food shortages in many parts of the world, as well as the threat of insufficient supplies in the near future, continues to stimulate more intensive agricultural investigation in a search for more productive alternatives. As a consequence, it appears that

we are about to embark on a new phase of agricultural research. Exactly what form it will take is still not known, but the reasons for this new approach are rapidly becoming apparent.

First, we have begun to observe a leveling off in yield increases brought about by the types of genetic manipulation that gave us such rapid and impressive yield increases during the "Green Revolution." It is as if we have reached a "yield plateau" with the current lines of research and crop selections. Large-scale use of single varieties (e.g., some of the International Rice Research Institute (IRRI) varieties of rice), with broad adaptability, produced major breakthroughs in yields. But it appears that these varieties have almost reached their maximum yield potentials. In many areas with specific soil and climatic conditions, they have not performed as well as hoped, especially on land more difficult to mechanize or irrigate. Thus we must begin to look for varieties with more specific adaptability and selected for specific environments, or else consider alternative cropping systems.

Second, most of the dramatic yield increases during the past few decades have been on the best agricultural lands—areas with good soil and easy water control. Future increases in production, therefore, will demand a new and innovative way of managing these highly productive lands, as well as looking for methods to make marginal lands increasingly productive. Only 20 percent of Asia rice land, for example, is irrigated, and the new high yielding rice varieties (which also require high levels of fertilizers, water use, and pest control) have not penetrated much beyond this boundary (16).

The third factor is the oil crisis. Oil prices continue to soar, and with them, the cost of fertilizers, pesticides, and fuel needed to build and run farm equipment and move irrigation water. Costs continue to mount for those inputs most responsible for achieving the dramatic yield increases of the "Green Revolution." We are faced with the necessity of having to consider other alternatives that might allow us to substitute innovative biological or agronomic practices and varieties for these high cost inputs. Multiple cropping offers one of the most important and promising of these alternatives.

CONCEPTS AND DEFINITIONS

Multiple cropping systems use management practices where the total crop production from a single piece of land is achieved by growing single crops in close sequence, growing several crops simultaneously, or combining single and mixed crops in some sequence. The most important aspect of multiple cropping is the intensification of crop production into additional dimensions. Multiple cropping includes the dimensions of time and space; for example, when two crops share the same space at the same time.

A classification of types of multiple cropping systems is presented in table 1. Note that special emphasis is placed on the distinction between intercropping, where two or more crops are grown at the same time, and sequential cropping, where two or more crops are grown on the same piece of land, but one following the other.

Some additional terms used in multiple cropping are presented in table 2. Agroforestry, as a particular type of intercropping system, will be discussed in some detail. Also, "mixed cropping," "polyculture," and "multiple cropping" will be used interchangeably in this review. By combining different aspects of simultaneous and sequential cropping systems, it is possible to visualize a truly complex pattern of different multiple cropping systems. This classification will be used throughout the following discussion, based on a symposium sponsored by the American Society of Agronomy, in support of the need to standardize terminology (34).

Table 1.—Definitions of the Principal Multiple Cropping Patterns

- **Multiple Cropping:** The intensification of cropping in time and space dimensions. Growing two or more crops on the same field in a year.
- **Intercropping:** Growing two or more crops *simultaneously* on the same field per year. Crop intensification is in both time and space dimensions. There is intercrop competition during all or part of crop growth. Farmers manage more than one crop at a time in the same field.
  - —*Mixed intercropping*: Growing two or more crops simultaneously with no distinct row arrangement.
  - —*Row intercropping*: growing two or more crops simultaneously with one or more crops planted in rows.
  - —*Strip intercropping*: Growing two or more crops simultaneously in different strips wide enough to permit independent cultivation but narrow enough for the crops to interact agronomically.
  - —*Relay intercropping*: Growing two or more crops simultaneously during part of each one's life cycle. A second crop is planted after the first crop has reached its reproductive stage of growth, but before it is ready for harvest.
- **Sequential Cropping:** Growing two or more crops in *sequence* on the same field per year. The succeeding crop is planted after the preceding one has been harvested. Crop intensification is only in the time dimension. There is no intercrop competition. Farmers manage only one crop at a time.
  - —*Double cropping*: Growing two crops a year in sequence.
  - —*Triple cropping*: Growing three crops a year in sequence.
  - —*Quadruple cropping*: Growing four crops a year in sequence.
  - —*Ratoon cropping*: Cultivating crop regrowth after harvest, although not necessarily for grain.

SOURCE: Andrews and Kassam, 1976 (5).

Table 2.—Related Terminology Used in Multiple Cropping Systems

Single Stands: The growing of one crop variety alone in pure stands at normal density. Synonymous with "solid planting," "sole cropping." Opposite of "multiple cropping."

Monoculture: The repetitive growing of the same crop on the same land.

Rotation: The repetitive growing of two or more sole crops or multiple cropping combinations on the same field.

Cropping Pattern: The yearly sequence and spatial arrangement of crops, or of crops and fallow on a given area.

Cropping System: The cropping patterns used on a farm and their interactions with farm resources, other farm enterprises, and available technology that determine their makeup.

Mixed Farming: Cropping systems that involve the raising of crops and animals.

Cropping Index: The number of crops grown per annum on a given area of land multiplied by 100.

Relative Yield Total (RYT): The sum of the intercropped yields divided by yields of sole crops. The same concept as land equivalent ratios. "Yield" can be measured as dry matter production, grain yield, nutrient uptake, energy, or protein production, as well as by market value of the crops.

Land Equivalent Ratios (LER): The ratio of the area needed under sole cropping to the one under intercropping to give equal amounts of yield at the same management level. The LER is the sum of the fractions of the yields of the intercrops relative to their sole-crop yields. It is equivalent to RYT, expressed in commercial yields.

Income Equivalent Ratio (IER): The ratio of the area needed under sole cropping to produce the same gross income as is obtained from 1 ha of intercropping at the same management level. The IER is the conversion of the LER into economic terms.

SOURCE: Sanchez, 1976 (39).

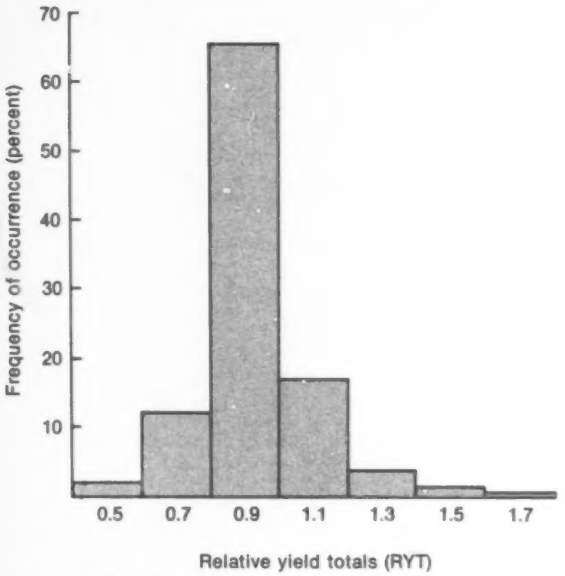
THE BASIS OF MULTIPLE CROPPING

Yield Advantages of Crop Mixtures

In areas of the world where multiple cropping is a common aspect of agroecosystem management, productivity generally is more stable and constant in the long term (24,45). Farmers often are able to achieve a combined production per unit area greater with a crop mixture than with an equal area divided among separate crop units. In such cases the Relative Yield Total (RYT) is greater than 1.0. It may be that each crop in the mixture yields slightly less than the monocultures, but the combined yield of the mixture on less total land area is the important aspect.

In one study (43), the results of 572 comparisons of crop mixtures demonstrated that the majority (66 percent) had RYTs close to 1.0, indicating no distinct advantage to the mixture (fig. 1). On the other hand, 20 percent of the mixtures had RYTs greater than 1.0, ranging up to 1.7, indicating advantages to the mixtures. Only 14 percent had less than 1.0, indicating distinct disadvantages. It must be remembered that most of the cases studied

Figure 1.—Distribution of the Relative Yield Totals of Mixtures Based on 572 Published Experiments



SOURCE: Trenbath, 1974 (43).

were experimental planting and not actual multiple cropping systems. Farmers would tend to choose the systems that yield more, as we have observed in traditional agroecosystems in the lowland tropical areas of southeastern Mexico (24,25).

The fact that advantageous mixtures do exist demonstrate the need for detailed research to take proper advantage of such systems. But for such systems to be considered as actual alternatives we need to understand thoroughly the biological and agronomic basis responsible for the observed response, as well as the advantages and disadvantages to their use. Before beginning a discussion of each aspect, a basic outline of such characteristics is presented, separated broadly into biological and physical aspects (table 3) and socioeconomic aspects (table 4). In many cases it is understood that there may be overlap between the two classifications, yet it is hoped that in the course of the following discussion that such aspects will be clarified.

Table 3.—Biological and Physical Factors: The Advantages and Disadvantages of Multiple Cropping Systems Compared to Sole-Cropping or Monoculture Systems (priority is not established)

Advantages

1. It is possible to obtain a better use of vertical space and time, imitating natural ecological patterns in regards to structure of the system, and permitting efficient capture of solar energy and nutrients.
2. Greater amounts of biomass (organic matter) can be returned to the system, sometimes even of better quality.
3. There exists a more efficient circulation of nutrients, including their "pumping" from the deeper soil profiles when deeper rooted shrubs or trees are included.
4. The damaging effects of wind sometimes can be reduced.
5. Systems can be designed that are appropriate for (but not restricted to) marginal areas because multiple cropping systems can better take advantage of variable soil, topography, and steeper slopes.
6. Multiple cropping systems are less subject to variability in climatic conditions, especially extremes of rainfall, temperature, or wind.
7. Reduction of water evaporation from the soil surface.
8. Increased microbial activity in the soil.
9. Avoidance or reduction of surface erosion.
10. Fertilizer use can be more efficient because of the more diverse and deeper root structure in the system.
11. Improved soil structure, avoiding the formation of a "hard pan" and promoting better aeration and filtration.
12. Legumes (as well as a few other plant families) are able to fix and incorporate nitrogen into the system.
13. Heavier mulch cover aids in weed control.
14. Better opportunities for biological control of insects and diseases.
15. Crop mixtures better permit the functioning of complex mutualisms and beneficial interactions between organisms.
16. Better use of time, with more crops per unit time in the same area.

Disadvantages

1. Competition between plants for light.
2. Competition between plants for soil nutrients.
3. Competition between plants for water.
4. Possibility for allelopathic influences between different crop plants due to plant-produced toxins.
5. Harvesting of one crop component may cause damage to the others.
6. It is very difficult to incorporate a fallow period into multiple cropping systems, especially when long lived tree species are included.
7. It is sometimes impossible, and many times very difficult, to mechanize multiple crop systems.
8. Increased evapotranspiration loss of water from the soil, caused by greater root volume and larger leaf surface area.
9. Possible over-extraction of nutrients, followed by their subsequent loss from the system with the increased exportation of agricultural or forest products.
10. Leaf, branch, fruit, or water-drop fall from taller elements in a mixed crop system can damage shorter ones.
11. Higher relative humidity in the air can favor disease outbreak, especially of fungi.
12. Possible proliferation of harmful animals (especially rodents and insects).

Table 4.—Social and Economic Factors: The Advantages and Disadvantages of Multiple Cropping Systems Compared to Sole-Cropping or Monoculture Systems (priority is not established)

Advantages

1. Depencence on one crop is avoided so that variability in prices, market, climate, and pests and diseases do not have such drastic effects on local economics.
2. Less need to import energy, pay for fertilizers, pay for externally produced materials, or depend on machinery.
3. Wildlife is favored, and with rational use it can be an important source of protein.
4. Greater flexibility of the distribution of labor over the year.
5. Recovery of investments can occur in much less time, especially where trees are combined with short term agricultural crops.
6. Harvest is spread over a longer period of time.
7. In areas and times of high unemployment, multiple cropping systems can use much more labor.
8. Farmers can produce a large variety of useful products, depending on the type and complexity of the multiple cropping systems, such as firewood, construction materials, flowers, honey, crops for home consumption, thus lowering the outflow of funds.
9. Certain multiple cropping systems permit a gradual change from destructive farming practices to more appropriate technologies, without a drop in productivity.
10. Multiple cropping can promote a return to the land, and its maintenance.
11. In systems which include trees and/or animals, such components can constitute a type of "savings" for the future, while short term crops satisfy immediate needs.
12. Because of their diverse nature, multiple cropping systems promote interdisciplinary activities, stimulate interchange and group activities, and lead to social cohesion in the long term.

Disadvantages

1. The systems are more complex and less understood agronomically and biologically. Statistical designs for experimental analysis are much more complex.
2. Yields sometimes are lower, providing only subsistence level production.
3. In many systems, multiple cropping is not considered to be economically efficient due to the complexity of activities necessary.
4. These systems require more hand labor, which can be considered a disadvantage in some circumstances.
5. Some mixed crop systems do not offer sufficient reward to lower income farmers to raise their standard of living.
6. For producers with limited economic resources, it may take longer to recover the entire initial investment.
7. Farmers initiating multiple cropping systems may encounter opposition from the prevalent social, economic, and political system.
8. There is a shortage of trained personnel (technical and scientific) capable of installing and managing multiple cropping systems.
9. There is a general lack of knowledge or understanding of multiple cropping by "decision makers," affecting especially funding for research to make such systems viable alternatives.

General Resource Use

The most commonly accepted reason explaining why it is possible to obtain better yields with crop mixtures is that the component crops differ in their growth requirements. Such combinations of components can be said to be "complementary" (46).

A mixture makes better overall use of available resources. Negative influences (e.g., competition for light, water, or nutrients) between the component members of a successful multiple cropping system would be reduced considerably. To maximize the advantages of such a system, it is important to maximize the degree to which one component complements another. With a greater range of requirements between different elements of the mixture, theoretically the greatest advantages would be achieved.

One way to achieve complementarity is by varying the crop components temporally—using sequential planting to achieve a multiple cropping system that ensures that antagonistic interactions between the components are avoided. Following a crop with another that has different growth requirements would enable the maximum use of resources. This concept has been used for a long time and is the basic rationale behind crop rotations.

The most advantageous use of soil, for example, would be to follow one crop with another that requires different soil nutrients. A subsequent crop would thus be able to absorb fertilizer residues left over from the previous crop, thus reducing the need for fertilizer applications. For the Eastern United States, it has been concluded (31) that double cropping systems such as soybeans after wheat or barley, or the production of silage crops after grain corn or sorghum, can function well.

Depending on the length of the growing season, numerous sequential plantings can take place during a single year. Such systems require special management, with timely harvest, use of proper varieties, alteration of the stand-

ard planting distance, special selection of herbicides so as to not create antagonisms or residual effects, and also the possibility of using no-tillage planting with certain of the row crops.

Another form of complementing different crop components is through an intensification of the sequential cropping system known as relay planting. The same avoidance of overlapping plant growth requirements is gained, as well as the avoidance of direct plant interference, by planting a second crop after the first one has completed the major part of its development, but before harvest. Relatively little research on relay cropping has been done in the United States, and most has demonstrated little if any yield advantage (31). On the other hand, in Mexico and Latin America innumerable examples of relay planting with definite yield advantages have been reported, especially for corn and beans (35,39).

Again, the important, and as yet little studied, aspect of relay planting success depends on the correct combinations of timing and varieties so as to avoid shading, nutrient competition, or inhibition brought about by toxicity produced by the decomposition of a previous crop residue.

Finally, maximum complementarity can be achieved by growing two or more crops simultaneously, either in rows, strips, or mixed, but taking advantage of the spatial arrangement of the different crops and knowledge of their individual growth requirements. Again, most examples of such systems come from outside the United States. One particularly well-documented example is a traditional corn, bean, and squash system in Tabasco, Mexico (4).

Corn is planted at a density of 50,000 plants/ha, climbing beans in the same hole at a density of 40,000 plants/ha, and the squash intermixed among the rows of corn and beans at a density of 3,330 plants/ha. All are planted at the same time in this case. Beans begin to mature first, using the corn stalks for support; the corn matures second; the squash is the last to mature. Aerial space is divided such that corn occupies the upper canopy, beans the middle, and squash covers the ground. Better weed control is achieved, and insect pests are largely controlled by natural enemies. Corn yield was significantly higher for the polyculture as compared to different densities of monocultures, but beans and squash suffered a distinct yield reduction (table 5). Interestingly, the LER (Land Equipment Ratio) value of 1.73 tells us that the sum of the yields in the mixture can only be equaled in monoculture by planting 1.73 times the area divided proportionally among the three sole crops.

Table 5.—Yields of Corn, Beans, and Squash (kg/ha) Planted in Polyculture as Compared to Low and High Densities of Each Crop in Monoculture

	Total grain or fruit yields				
Crop	Monocultures				Polyculture
Corn:					
Density	33,300	40,000	66,600	100,000	50,000
Yield	990	1,150	1,230	1,170	1,720
Beans:					
Density	56,800	64,000	100,000	133,200	40,000
Yield	425	740	610	695	110
Squash:					
Density	1,200	1,875	7,500	30,000	3,330
Yield	15	250	430	225	80
Crop	Total biomass dry weight				
Corn	2,822.9	3,119.4	4,477.5	4,870.9	5,927.2
Beans	852.9	895.1	842.6	1,390.4	253.1
Squash	240.9	940.9	1,254.0	801.9	478.3
				Total Polyculture Biomass	6,658.6

LER (Land Equipment Ratio) = $\frac{\text{Sum of yields of each polyculture}}{\text{Sum of highest yield each monoculture}}$

$$LER = \frac{1{,}720}{1{,}230} + \frac{110}{740} + \frac{80}{430}$$

LER = 1.73

SOURCE: Amador, 1980 (13).

The advantage of producing a greater yield altogether on less land is obvious. The much higher total yield of biomass in the mixture is also important because much of this organic matter is returned to the soil, bringing important consequences in soil fertility, humidity conservation, microbial activity, etc., all related to the success of the following crops. Currently,

studies are being conducted to determine if the higher yields are the result of more efficient resource use, or if in fact some mutually beneficial effect between crop components is taking place, for example, the bean producing nitrogen that the corn can absorb (12). This example demonstrates the enormous potential that multiple cropping systems offer for the future.

Specific Resource Use, Conservation, and Management

An intensified land-use system of agriculture will certainly put greater pressures on the available natural resources of our crop and rangelands. Considerable discussion has focused on the harmful or beneficial aspects of this intensification, and a review of some of the more important aspects can aid greatly in understanding this problem:

1) *Microclimate and Light*: In any agroecosystem, a very important aspect of productivity is related to the amount of light converted directly to carbohydrate, hence to vegetative material, through photosynthesis. Each cropping system has a photosynthetic potential, based on its capacity of conversion (2). Monocultures, especially of annuals, generally have a lower potential because either the plant cover is not complete, or the soil is occupied only during one short season, leaving the surface bare of photosynthetic capacity until the next crop is planted. Light is not like other resources, where a reservoir exists and the plants tap it as the need arises. Rather, it has to be used when it is available, thus leaf area becomes a very important factor. A multi-layered polyculture would be able to capture much more light energy, raising efficiency, and potentially, production.

Apart from the quantity of light absorbed, its quality is also important. Light that has passed through a leaf layer is altered as certain light waves are absorbed and others penetrate. Plants in the lower layers of the canopy need to be adapted to this alteration—an aspect well studied only in natural vegetation (7). For cropping systems, light has been studied in detail only for monoculture systems (2) from the point of view of increasing effective photosynthetic leaf area for the single crop. By manipulating species with different light requirements, greater photosynthetic potential can be achieved. This is made easier by using dominant species in the polyculture that do not develop a closed canopy, allowing considerable penetration to the next levels. The most shade-tolerant plants should be in the lowest levels. In such a system, the soil surface is in essence completely covered by plants. This manipulation of plant architecture has been studied in detail ecologically (28) and has considerable application in multiple cropping systems.

Other aspects of the crop microclimate are also affected. Crops in the lower layers would be subject to less water stress, but care must be taken that root system competition for water does not become a problem. Water loss by soil surface evaporation could be reduced, but transpiration from leaf surfaces might be increased in the crop mixture. Soil temperatures would be lowered, an advantage especially in warmer and drier environments, aiding in the conservation and buildup of organic matter in the soil. Protection from wind would be provided for the lower canopy species. Care would need to be taken that the increased humidity in the lower canopies does not promote higher incidence of certain diseases, especially fungi, either of the roots or foilage.

2. *Soil-Plant Relations in Multiple Cropping Systems*: Any time that we try to combine two or more crops simultaneously in one area, there exists the possibility for complex interactions between the plants and their soil environment (39). When total complementarity is achieved, the roots of the component species occupy different soil horizons, reducing considerably the potential competition between species and increasing the efficiency of total nutrient uptake. In combinations of deep-rooted with shallow-rooted species, especially when trees are planted with grasses or annual crops, the trees are capable of absorbing uncaptured nutrients as they are leached into the

soil. Then, through their transport to foliage, they can be deposited on the soil surface again as the leaves drop (47).

Intercropping systems have been shown to extract more nutrients from the soil than do single crop plantings per unit area of land. In a very complete study with corn and pigeon peas in Trinidad (19) (table 6), various parameters of crop response were measured. The highest single crop yields of grain were obtained in monocultures, but by adding yields of two crops planted mixed or in intercropped rows, Relative Yield Totals (RYT) were higher. Total dry matter production was higher in the mixtures as well. The most interesting aspect is the uptake of nutrients (N, P, K, Ca, and Mg). The total uptake is based on the sum of the two crops together, and in all cases the total nutrient content of the dry matter production was higher for the mixtures, demonstrating the greater extractive capacity of the multiple cropping system. Apparently, for corn and pigeon peas, row intercropping gave the best results, demonstrating that at times two crops together can negatively influence each other, but the total yield makes up for the reduction. Each crop mixture needs to be examined in detail.

The greater uptake of nutrients in crop mixtures could deplete the soil more rapidly. But an aspect of multiple cropping that needs to be considered is what proportion of this nutrient content is removed from the system with the harvest, as compared to the part reincorporated back into the system. In table 7, a corn/bean polyculture is compared to a corn monoculture. Total biomass production, as well as yield removed from the system, is considerably higher from the mixture (10.24 tons/ha versus 6.68 tons/ha total biomass). The percentage of this total that leaves the system is slightly lower for the mixture (61 percent versu 66 percent), but the actual amount of organic matter returned to the soil in the polyculture (3.98 tons/ha) as compared to the sole

Table 6.—Effects of Mixed and Row Intercropping on Yields and Nutrient Uptake of Corn (C) and Pigeon Peas (PP) in St. Augustine, Trinidad, Expressed as Relative Yield Totals (RYT)

	Sole crop		*Mixed intercrop*			*Row intercrop*		
Parameter	C	PP	C	PP	RYT	C	PP	RYT
Grain yields (tons/ha)	3.1	1.9	2.0	1.7	1.54	2.6	1.8	1.78
Total Dry Matter (tons/ha)	6.4	5.1	4.2	3.8	1.40	5.0	4.9	1.74
N uptake (kg/ha)	66.0	119.0	48.0	100.0	1.56	54.0	127.0	1.88
P uptake (kg/ha)	13.0	6.0	9.0	5.0	1.52	11.0	7.0	2.01
K uptake (kg/ha)	51.0	37.0	37.0	32.0	1.59	46.0	33.0	1.79
Ca uptake (kg/ha)	10.0	22.0	10.0	15.0	1.68	9.0	19.0	1.76
Mg uptake (kg/ha)	12.0	14.0	9.0	8.0	1.32	9.0	12.0	1.61

SOURCE: Adapted from Dalia, 1974, (19), cited by Sanchez, 1976, (39).

Table 7.—Biomass Distribution (in tons/ha) of Dry Matter in a Corn/Bean Polyculture as Compared to a Corn Monoculture, in Tacotalpa, Tabasco, Mexico

Crop	Roots	Crown	Leaves and stem	Grain[a]	(A) Total	(B) Removed matter	(*B*) (*A*) percent	(A)-(B) Total reincorporated
Corn plus	0.49	0.60	2.29	4.76[b]	10.24	6.26	61%	3.98
Beans	0.15	0.00	0.45	1.50[b]				
Corn Alone	0.34	0.41	1.57	4.36[b]	6.68	4.36	65 %	2.32

[a]Weight of grain of corn is unhusked, including cob and husk, in the manner that the harvest is removed from the field in this region.
[b]Indicates the removed portion of the biomass.

SOURCE: Adapted from Gliessman and Amador, 1979 (24)

crop (2.32 tons/ha) demonstrates that although more material is produced by the intercrop system, a greater amount returns to this system. This possibly offsets any increase in extraction of soil nutrients and permits the long-term management of the system.

Another way to increase the return of nutrients to the system is to plant "nurse plants." These plants do not contribute directly to the biomass harvested and removed from the system, but their capacity to capture nutrients and continually recycle them in the soil would be an advantage. Local farmers in Tabasco, Mexico, use this concept in the management of weeds (14), leaving those that don't interfere with the crops and removing those that are harmful. This practice also provides a constant cover over the soil and helps maintain better soil structure, conserves water, fosters more microbial activity, and over the long run, requires fewer chemical fertilizers. By including plants that "trap" nutrients, such as legumes, such benefits can be improved even more. The widespread use of legume trees for shade in coffee and cocoa plantations is a classic example (27).

3. *Water Use in Multiple Cropping Systems*: Any discussion of water use should consider rooting patterns. In multiple cropping systems, especially with several crops with differently arrayed root systems, a greater volume of the soil typically is occupied and thus water use efficiency is higher. This is useful, on the one hand, in areas where water supplies are limited. It also helps make more complete use of costly irrigation water. It has been proposed that cover crops in orchards stimulate deeper rooting by the trees (10). Different peak periods of water use in the crop mixtures would avoid competition and increase overall water use efficiency (8). A crop such as corn that uses relatively little water in its early stages of development could be interplanted with an early maturing crop that could take advantage of the unused moisture (30).

In areas where water is severely limited, care must be taken not to plant crops with overlapping water requirements because in dry years one member of the mixture could be outcompeted by the other (36). Combining two crops with slightly overlapping water needs, on the other hand, could be used to an advantage in areas with widely fluctuating rainfall regimes. In a dry year, one component would be favored, and in a wet year the other, guaranteeing profitable harvests of at least one crop every year. Studies on water availability in each region, coupled with studies of water needs of each component crop of multiple cropping systems, are critical for proper management.

The important effects of multiple cropping on the conservation of water and soil are primarily achieved through the maintenance of a more complete vegetative cover over the soil (26,40). It is important to remember that apart from improving cover while the crop is growing, multiple cropping systems aim toward maintaining this cover between harvests. This is achieved by reducing the time between harvest and replanting in sequential systems, planting a new crop into another in relay cropping, and continually interplanting in an intercropped system. The use of trees, either as windbreaks, for soil stabilization on eroded hillsides, or in areas subject to desertification, can be enhanced greatly by combining them with crops or pasture grasses (see discussion on Agroforestry).

In summary, although it appears that multiple cropping systems use more water, their ability to obtain water not available to monoculture, use the water more efficiently, and contribute significantly to soil conservation, demonstrate a further potential for their more widespread use.

4. *Pest, Disease, and Weed Relations*: As discussed, possibilities exist for multiple cropping systems to be both advantageous and disadvantageous in relation to problems of pests, diseases, and weeds (29,32). The problem has to do with the great complexity of environmental factors and their dynamic interactions within the cropping systems. Where capital is not available or technical assistance has not been accepted, we observe that the main means of pest, disease, and weed control is through bio-

logical control, and through the management of a great diversity of cropping patterns, both in time and space (23).

It has been suggested that multiple cropping systems permit such a control because they are much less subject to attack (6,29,38). This comes about because the mixed cropping system: 1) prevents spread of diseases and pests by separating susceptible plants; 2) one species sometimes serves as a trap crop, protecting the others; 3) associated species sometimes serve as a repellant of the pest or disease to which the other crops are subject; and 4) a greater abundance of natural predators or parasites of pests are present due to a higher diversity of adequate microsites and alternate prey.

However, there are also reasons why a multiple cropping system may be more susceptible to attack: 1) reduced cultivation and greater shading due to the presence of associated species, 2) associated crops serve as alternate hosts, and 3) crop residues from one crop may serve as a source of inoculum for the others. All of these advantages and disadvantages can exist, and further study is necessary to achieve the combinations that give the most positive results.

A few examples might serve to demonstrate the potential of multiple cropping for biological control. In one study (22), it was shown that the planting of a locally used medicinal herb (Chenodium ambrosioides) in sequence with corn or beans reduced the incidence of nematode populations in the soil, demonstrating a potential for reducing attack on the roots of the food crops. The herb added substances toxic to the nematodes into the soil. In another study, yields of cotton untreated with insecticides, but interplanted with sorghum, were 24 percent higher than sprayed monocultures. The reason was that sorghum served as a microhabitat for cotton bollworm predators (18). In another case, fall army worms were less a problem on corn associated with bush beans than on pure-stand corn (21). Beans intercropped with corn were attacked less by rust compared to beans in pure stands, probably because corn functions as a barrier to the dissemination of the fungal spores (41).

Weeds, on the other hand, present another problem. It has been reported that weeds are much less a problem in multiple cropping systems, especially in intercropping (32), because the space normally available to weeds is filled with other crops. The aggressive nature of weeds is well known (9), but recent work has begun to show that weeds can fill an important ecological role in cropping systems, by capturing unused nutrients, protecting the soil, altering soil fauna and flora, serving as trap plants for pests and disease, and changing the microhabitat to allow for high populations of pest predators and parasites (3,17). In rural tropical Mexico, farmers understand and use a "non-weed" concept (14), where each is classified according to positive or negative effects. We need to understand in more detail the biological functions of each component of the agroecosystem to establish the structure that will allow adequate weed, pest, and disease control. If part of this control can be achieved by merely manipulating the crop mixture in time and space, great strides toward more efficient agricultural management can be made.

5. *Mutualisms and Crop Coexistence*: In natural ecosystems, a great number of interactions between different species are mutually beneficial for those organisms involved, leading us to believe that there is a strong selective pressure operating to select combinations that coexist rather than compete (37). On the long term, such a coexistence permits a more efficient use of resources, with the component organisms aiding one another rather than interacting negatively. This frees more energy for growth and reproduction.

To a certain extent, nurse crops or companion plants function in this way. Legumes, because of their symbiosis with nitrogen-fixing bacteria, can coexist with corn without competing for nitrogen. In fact, part of the legume's nitrogen may be available for the corn (12), reducing overall need for fertilizers. Studies with coffee and cocoa shade trees have demon-

strated the same relationship; the trees provide shade, nitrogen, and an organic mulch over the soil.

As mentioned, the presence of one crop may have beneficial effects on others through alteration in the microclimate, pest and disease protection, etc. Thus, apart from looking for crops that complement one another by avoiding overlap in requirements, we need also to look for crops that are interdependent and that mutually benefit from the association. This will be a very stimulating challenge for crop selection programs.

6. *Use of Space and Time*: One of the most important aspects of the management of multiple cropping systems is the facility they offer for the intensification of production through manipulation of space and time. By achieving the most ideal combination of the two, we will achieve the greatest productivity. On the one hand, we attempt to occupy the available resource space as efficiently as possible, combining species that complement each other, yet attempting to avoid overlaps that lead to negative interactions.

Resource use in space is then combined with its use in time, trying to achieve constant use of the resources available. For this reason, multiple cropping systems are intensified by sequential, relay, and mixed planting that establish constant resource use within the environmental limits imposed by the ecological conditions of each region. In this sense, we can even visualize the possibility of including cold resistant trees in association with annual crops or pasture, so that during the winter the trees continue to occupy the area. Thus, any yield reduction during the normal frost-free growing season is compensated for by the long-term tree production.

Additionally, multiple cropping systems permit greater stability in production, despite variability in climate or physical factors in the planting area. Whatever the conditions in one location and for one growing season, at least one member of the multiple cropping system will succeed. Since most of the better drained and structured soils are already in production, the more marginal lands will require special technology to make them produce. We cannot consider for the moment massive programs of soil and water manipulation needed to install mechanized high-yielding monocultures. To do so is economically, if not ecologically, prohibitive. The basic framework is available in multiple cropping. Innovative combinations need to be searched for and tested.

Agroforestry: A Multiple Cropping System

Agroforestry is a technology of land management that combines trees with agricultural crops, with animals, or any combination of the two. Combinations can be simultaneous, or staggered in either time and space. The major objective of agroforestry is to optimize production for each unit of surface area, keeping in mind the need to maintain long-term yield (11,13,42). Small-scale, traditional agriculture has always included trees as integrated elements of farm management, but only recently has interest been revitalized in the application of agroforestry practices into modern agriculture.

The renewal of interest in agroforestry is based on many of the same reasons for multiple cropping systems in general: the ever-increasing demand for production, yet the rising cost of obtaining it. The explosive demand for firewood and lumber has placed incredible pressures on the world's forests, especially in tropical and subtropical regions. Deforestation continues at an accelerated rate (20,44). But programs of reforestation or multiple-use forest management do not satisfy basic needs for food, clothing, and other necessities that come from crop and range lands. It would seem logical that these pressures for both forest and agricultural products would stimulate their combination in agroforestry systems.

Agroforestry practices can be broadly classified into three types (15): 1) combined agrosilvicultural (crop plus trees) systems, 2) combined forestry and grazing, and 3) simultaneous combinations of forestry with crops and grazing. Examples of each of these classifications

are presented in table 8. The focus varies from soil improvement, erosion control, wind breaks, and shade to lumber, firewood, and reforestation. The combinations are essentially unlimited, depending on the needs of each region. At first glance it might appear that agroforestry systems are most applicable on marginal lands, on steep slopes, poor soils, or areas with widely fluctuating rainfall regimes. But agroforestry should also be considered for widespread application, even on prime agricultural or grazing land, because production needs to be increased—both by opening up new areas and by looking for innovative ways to increase productivity of lands already in use.

The principle limitations to widespread use of agroforestry practices are economic and technological. Ecologically, the advantages are well known, but technically we still do not have the information necessary to begin immediate implementation. With the present focus in agriculture aimed at maximizing single crop yields, there is a lack of acceptance of the idea that yields need to be thought of more on a long-term, diversified basis. Agricultural research has not yet accepted the challenge that an integrated focus to forest and farm management requires.

Socioeconomic Implications of Multiple Cropping Systems: Perspectives for the Future

In all of the aspects of multiple cropping systems that this review has considered—yield, resource use, pest and disease control, weeds, use of space and time, types of planting systems—much of the evidence indicates that generally there are more advantages than disadvantages of a biological, physical, or agronomic nature. But we need to consider the social and economic implications of the possible more widespread use of multiple cropping systems in present day agriculture.

As was seen in table 4, the types of advantages derived from multiple cropping are many and varied. With a greater diversity of crops,

Table 8.—Classification and Examples of Agroforestry Technologies

Combined agrosilvicultural systems (trees with crops):

1. Agrosilviculture—establishment of trees, intercropped with agricultural crops during initial stages of tree growth, until tree canopies close and force the elimination of the crops. Production available in early stages of tree development, and cultivation activities simultaneously benefit both crops and trees.
2. Forest trees of commercial value in crop systems. Maintain trees in crop areas, either planted or natural, at low densities that do not interfere, yet provide value in the future.
3. Fruit trees in crop systems. A system that allows fruit production and grain or vegetable production simultaneously.
4. Trees that serve as shade for certain crops or improve the soil through nitrogen fixation, organic matter incorporation, mulch, and microclimate modification.
5. Trees used as hedgerows, fence lines, or windbreaks around cropping areas, where management is intimately linked with the needs of the crops.
6. Trees around rivers, lakes, or artificial reservoirs or tanks, integrated with fish or waterfowl management, providing shade, food, and roosting.

Combined forestry and grazing systems (trees with grasses):

1. Grazing or forage production takes place within forestry plantations, aiding in avoiding weed or brush build up, lowering fire risk.
2. Grazing or forage production in young natural forests, with same advantages as above.
3. Forest trees of commercial value in pastures, either planted or natural, at densities that do not interfere with the pasture species.
4. Timber trees in pasture, either planted or natural, with the capacity to fix nitrogen and improve soil, thus lowering the need to fertilize and provide commercial value.
5. Trees in pastures that provide shade for the animals and aid in improving the soil through nitrogen fixation and nutrient extraction from deeper soil levels.
6. Trees, either in or around pastures, or in forests, that produce foliage of forage value for animal consumption. Can allow the reduction of feed supplement for animals.
7. Fruit trees in pastures, allowing for commercial production of both fruits and animals.
8. Trees around pastures as hedgerows, fence lines, or windbreaks.

Simultaneous combinations of forestry with crops and grazing:

1. Forest plantations planted with crops and grasses, permitting the management of grazing animals, either free to wander or enclosed in specific areas. Especially adapted to smaller animals, such as ducks or pigs. Requires close control of activities and use of specific crops.
2. Trees associated with crops and grazing, either planted or natural, in densities that will not adversely influence the crops. Trees scattered in and around cropping areas can be periodically pruned and used as forage for animals, with the timber harvestable at some later date.
3. Hedgerows or living fence lines around rural communities, serving as shade, windbreak, property divisions, forage, fruits, timber, and firewood. In this sense, the system is truly multiple use.

SOURCE: Combe and Budowski, 1979 (15).

a farmer is less affected by market fluctuations and is able to shift from one crop to another depending on price and demand. At the same time, the harvest is spread out over a longer period of time. Less dependence on outside energy sources has obvious advantages, especially in areas where capital is limited. Labor, instead of being concentrated in certain periods of the year, can be more evenly distributed, an important consideration in relation to the migrant farm worker problem. In times of higher unemployment, multiple cropping systems can offer more and steadier work.

Most of the economic disadvantages are derived from our lack of experience and knowledge with multiple cropping systems. Reported lower yields, complexity of management activities, higher labor demands, and the difficulty in mechanizing such systems are all important factors that discourage modern farmers from participating in multiple cropping practices.

An important aspect of this resistance comes from the emphasis on large profits that governs so much of modern agriculture today. Maximum profits in the short term, rather than concern with maintaining constant income in the long term, governs the decisionmaking process on most American farms today. But with the incredible rise in farm costs, a new focus is necessary. All of these increases cannot be passed on to the consumer. Many of the advantages of multiple cropping systems definitely need to be stressed more for use on farms today. Smaller farms, with a greater diversity of products and activities, can function quite profitably because they are less dependent on high-cost energy inputs. Lower costs mean food can be produced at a lower price, the benefits being transferred to the general population.

Smaller farms would require more farmers. To a certain extent multiple cropping systems mean a return to the land, with the incentives necessary to keep the farmers there. The great diversity of activities in multiple cropping systems would promote an increase in interdisciplinary activities in their investigation, installation, management, and use in agriculture. This stimulation of interchange and collaboration can, in the long term, lead to greater social cohesion. Rural regions might once again take on the social importance they enjoyed in the past. The problems of lack of trained personnel, and social, political, and economic restrictions on multiple cropping systems, all can be overcome by thorough and conscientious programs of research aimed at determining the proper methods, varieties, and practices necessary.

The belief that multiple cropping is only suitable for marginal or underdeveloped regions ignores the fact that just a relatively short time ago, such systems were the most common type of agriculture. Only recently have they been replaced by monoculture systems dependent on the use of massive quantities of inexpensive high energy inputs. For the moment, this time has passed and we need to learn from the past to reshape agriculture for the future. This will be a great challenge for agricultural research.

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Chapter VI

Development of Low Water and Low Nitrogen Requiring Plant Ecosystems for Arid Land Developing Countries

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Contents

	Page
Abstract	87
Introduction	87
Beneficial Aspects of Semiarid Plant Production Technologies on Semiarid Developing Countries	88
Where Technology is Used and Stage of Development (Subsistence, Commercial, or Research)	89
Development of Tree Legumes for Fuelwood	89
Use of Nitrogen Fixing Trees to Increase Soil Fertility	89
Development of Cash Crops on Semiarid Lands	90
Production of Livestock Food and Forage	91
Intercropping Traditional Food Staples With Arid-Adapted Legumes to Sustain High Food Staple Yields	92
Slowing the Spread of Desertification in Arid Regions	93
Fertilizer, Pesticide, Irrigation, and Machinery Requirements	93
Irrigation Requirements	93
Fertilizer Requirements	93
Pesticide Requirements	94
Machinery Requirements	94
Research, Development, and Implementation of Arid-Adapted Plant Ecosystem Production Technologies	95
Constraints Facing Development and Implementation of Arid-Adapted Plant Production Technologies	98
Effect of Technology Implementation on Capital, Labor, and Land Requirements	99
Impact of Wide-Scale Technology Implementation on the Socioeconomic Structure of Agriculture in Developing Countries	100
References	101
Work Statement	103

Table

Table No.	Page
1. Outline of Research Procedure	96

Chapter VI

Development of Low Water and Nitrogen Requiring Plant Ecosystems for Arid Land Developing Countries

ABSTRACT

This paper describes a low industrial input, commodity-oriented approach to stimulating economies of arid land countries using arid-adapted plant species. It suggests legume tree biomass farms using *Acacia, Leucaena,* and *Prosopis* genera to provide increased fuelwood. Increased soil fertility and ensuing water use efficiency could be achieved by using deeply rooted, drought-adapted species such as *Acacia albida* and *Prosopis cineraria* that fix nitrogen. Arid-adapted shrubs such as jojoba (*Simmondsia chinensis*), and guayule (*Parthenium argentatum*) could provide stable production of cash crops. *Prosopis* and *Acacia* pods, atriplex forage, *Leucaena* forage, and cactus pads could increase livestock food supplies. Increased production of traditional food staples such as millet, sorghum and peanuts can be achieved by intercropping them with arid-adapted legumes. Aggressive management of these plants could help reduce the spread of desertification.

Little government support has been made available for these activities despite their widespread use by indigenous farmers at subsistence levels. A research and development program is suggested that would establish living germplasm collections and select and propagate superior clones. Several months after stand establishment, these plant systems can be grown without supplemental irrigation by using ground water within 10 m of the surface or by using a minimum of 250 mm annual rainfall. Phosphate fertilizer, micronutrients, and rhizobial inoculation are required, but the nitrogen needs will be provided by nitrogen fixing plants. Less machinery will be needed to till these systems.

Wide-scale implementation of these systems would greatly enhance agricultural productivity at the local level, where it is most needed, and indirectly stimulate nonagricultural sectors of the economy. The increased economic well-being of farming classes could lead to decreased political unrest and greater stability of governments in arid lands. Foreign policy efforts to strengthen the peace by buildup of military hardware systems has proven futile in Ethiopia, Iran, and Iraq. Development of arid land plant production systems is a viable alternative to enhancing peace in politically volatile arid land countries.

INTRODUCTION

This document was prepared at the request of the Office of Technology Assessment (OTA) of the U.S. Congress to provide guidance in development of low energy, nitrogen, and machinery requiring agricultural systems for semi-arid developing countries. The format closely follows OTA's specific issues and questions. For the convenience of the reader, these requests are reproduced in appendix A.

Identifying plant physiological, morphological, and ecological characters that lend them-

selves to a minimal machinery, capital, and fossil fuel input is the subject of a paper by Felker and Bandurski (14) in which orchards of leguminous trees were suggested to most closely approximate an ideal system for minimizing industrial inputs. Other closely related shrub ecosystems have been suggested to achieve similar objectives (32). Identification of arid land plant species that would lead to more stable and productive ecosystems has been intensively investigated by Felger (11). Recent review volumes (42) and symposia (27,6) have dealt at length with arid land plant resources. This document attempts to synthesize the knowledge of arid land plant species, focusing on minimal energy input agriculture and a pragmatic commodity-oriented approach designed to provide major needs such as fuel, forage, and food staples required for arid land economies.

BENEFICIAL ASPECTS OF SEMIARID PLANT PRODUCTION TECHNOLOGIES ON SEMIARID DEVELOPING COUNTRIES

Development of leguminous trees (14) and associated semiarid ecosystem plant components such as saltbush (*Atriplex* spp.) (19), leucaena (*Leucaena leucocephala*) (15), cactus (*Opuntia* and *Cereus* spp.) (33,52), jojoba (*Simmondsia chinensis*) (23), and guayule (*Parthenium argentatum*) (50) can make a significant contribution to meeting the major commodity needs of people in semiarid developing countries. Some of the main biological needs and appropriate approaches to supplying them are as follows:

1. **Need:** increased availability of inexpensive fuelwood.
   Approach: use of leguminous tree biomass farms with *Prosopis, Leucaena,* and *Acacia* species.
2. **Need:** increased soil fertility to triple or quadruple water use efficiencies of food staples so that productivity is water-limited and not fertility-limited.
   Approach: use locally respected, drought-adapted, nitrogen-fixing legume tree such as *Acacia albida* and *Prosopis cineraria,* use shrubby legumes such as *Dalea* species, and use perennial arid-adapted herbaceous legume such as *Zornia* and *Tephrosia.*
3. **Need:** production of cash crops for farmers and for foreign exchange.
   Approach: use perennial arid-adapted plants, such as jojoba, guayule and high value, drought-adapted annuals, and ephemerals, such as sesame when grown in conjunction or rotation with arid-adapted nitrogen fixers.
4. **Need:** production of livestock food and forage.
   Approach: use arid-adapted, salt-tolerant shrubs, such as saltbush *(Atriplex* species) in conjunction with high water to dry matter conversion plant specialists, such as spineless cactus (*Opuntia ficus-indica*) and high protein and/or sugar content pods of leguminous tree species of *Acacia tortilis, Acacia albida,* and *Prosopis* spp.
5. **Need:** sustained production of traditional food staples, such as millet, sorghum, groundnuts, and cowpeas.
   Approach: intercrop the annual staples with nitrogen fixing trees previously demonstrated to stimulate annual legume yields such as the association with *Acacia albida* and peanuts.
6. **Need:** slow the spread of desertification.
   Approach: when intensive management of forage, fuelwood, and staple products are carried out as outlined above, desertification will slow.

WHERE TECHNOLOGY IS USED AND STAGE OF DEVELOPMENT (SUBSISTENCE, COMMERCIAL, OR RESEARCH)

Development of Tree Legumes for Fuelwood

Areas of use: *Prosopis alba* and *P. nigra* were reported to have fired industrial boilers and steam locomotives during World War II in Argentina (10). In Chile, the leguminous trees chanar (*Geoffrea decorticans*) and espino (*Acacia caven*) have been widely harvested by Indians and present day subsistence farmers for fuel (2). Mesquite wood and charcoal (*Prosopis* species) is highly esteemed and widely used in the Southwestern United States in steakhouses for barbecues and home heating. From 1956 to 1965, 78,000 metric tons of mesquite charcoal and 200,000 m^3 of mesquite firewood were recorded as items of commerce in Mexico (29). In the Jodphur state of India, *Prosopis* was declared the "royal plant" because it provided the bulk of the fuel to the local population (20). *Acacia* forests are harvested along the Nile 400 km upstream from Khartoum, Sudan, and brought to Khartoum for brick making and other industrial uses (24). In the Sahelian zones of Africa, many of the *Acacia* species such as *A. tortilis, A. seyal,* and *A. senegal* are consumed for woody biofuel.

Research organizations: The Central Arid Zone Research Institute in Jodphur has been conducting research on leguminous trees as sources of biofuels since the early 1940s (1). Their work is meagerly documented in the scientific literature and, from the lack of recent papers in the literature, their current research on tree legumes does not appear to be very active.

The Forestry Research Institute in Khartoum, Sudan, has received about $200,000 from the International Development Research Center (Ottawa) to evaluate *Prosopis* species under 200, 300, and 400 mm annual rainfall regimes. Much of the seed material for this experiment was supplied by the University of California-Riverside mesquite project. The United Nations Development Program (UNDP) provided support for Felker to supply seeds, mesquite rhizobia, plants, containers, and consultation to conduct varietal trials with 30 selections of leguminous trees (most *Prosopis*) in the Sudan at the Forestry Research Institute. Over 400 acres of *Prosopis* have been planted along irrigation canals in the Sudan courtesy of the Sudan Council of Churches to prevent sand from blowing into and filling the canals (26).

Dr. J. Brewbaker at the University of Hawaii has been conducting extensive research in Hawaii, Colombia, and the Philippines, on the development of leucaena as a biofuel crop. In the United States, the U.S. Department of Energy has funded research on *Prosopis* under Felker at the University of California-Riverside to develop an arid-adapted germplasm collection; to evaluate the collections in field conditions under drought, heat, and frost stress; to study nitrogen fixation and salt tolerance; and to clonally propagate outstanding single trees.

Use of Nitrogen Fixing Trees to Increase Soil Fertility

Areas of use: *Prosopis cineraria* has been used on a subsistence level by farmers in the India-Pakistan region to increase the yields of their pearl millet crops. Soil chemistry studies (46) corroborated increased nutrient contents and forage yields under *P. cineraria* trees versus other trees and open control areas. *Acacia albida* is widely used on a subsistence level in the West African countries of Senegal, Upper Volta, Mali, Niger, and Chad to increase the yields of sorghum, millet, and peanuts grown beneath the tree canopies (12). *Parkia biglobosa* was observed by this author growing in sorghum fields in a 400 mm annual rainfall regime where farmers stated the *Parkia* also increased the yields of their crops.

Yields of grasses and forbs grown in a growth chamber on soil from beneath mesquite canopies were four times greater than herbage yields grown on soils from outside mesquite canopy cover (49). The stimulation of forage yields after mesquite removal in the Southwest-

ern United States is probably due to increases in soil fertility supported by nitrogen fixation and reduction in competition for water. Mesquite nitrogen fixation and soil fertility increases on the 72 million acres (38) presently occupied by mesquite in the Southwestern United States is an unrecognized resource. Leucaena (*Leucaena leucocephala*) has been widely used in the Philippines in rotation with other crops, as a companion crop, and as a green manure with other crops to increase soil fertility.

Research organizations: Dr. Y. Dommergue, working for ORSTOM in Dakar, Senegal, West Africa, has conducted rhizobial inoculation trials with many African Acacias including *Acacia albida* and at this writing is actively involved in nitrogen fixation aspects of semiarid soils. Dr. Habish at the University of Khartoum, Sudan, published excellent papers on characterization of *Acacia*-rhizobia symbioses (21), but is now a dean at the University and no longer actively involved in research. A University of Arizona group, funded by the National Science Foundation (NSF), with Dr. Pepper as principal investigator, is collecting and characterizing rhizobia strains from many arid-adapted legumes.

A three-year $650,000 NSF grant has been awarded to study nitrogen cycling in a mesquite dominated desert ecosystem in southern California. This project involves: 1) an ecology group headed by Dr. Philip Rundel at the University of California, Irvine, that is conducting dry matter productivity analyses; 2) a University of California-Riverside soils group headed by Dr. Wesley Jarrell, that is converting the dry matter productivity measurements of the Irvine group into nitrogen productivity and conducting soil moisture profile measurements with 20 ft deep neutron probes, quantitating soil chemical characteristics on and around the site, quantitating denitrification, and developing *in situ* acetylene assays; and 3) a Washington University (St. Louis) group headed by Dr. D. H. Kohl that is correlating the above-mentioned findings with natural abundance $^{15}N^{14}N$ measurements to develop qualitative and perhaps semiquantitative assays of nitrogen fixation from dried plant samples.

The Department of Energy has funded studies on cross-inoculation of 13 *Prosopis* species (15), has conducted greenhouse studies of the effect of heat and drought stress on *Prosopis* nitrogen fixation, and has developed models comparing efficiencies of water and nitrogen inputs to increasing productivity of semiarid rangelands (16). USDA scientists have demonstrated that fertility can dramatically increase water use efficiency of rangeland species in a 10-year study on Montana rangelands (51). The USAID-supported Niftal group at the University of Hawaii maintains large stocks of rhizobia. Basak and Goyal (3) at the Central Arid Zone Research Institute at Jodphur have published cross-inoculation data and temperature and salinity tolerance characteristics for rhizobia for semiarid adapted leguminous trees in India.

Development of Cash Crops on Semiarid Lands

Areas of use: Jojoba (*Simmondsia chinensis*), a non-legume, is one of the most promising cash crops for arid lands. Jojoba seeds contain a rancidity-resistant, non-allergenic, liquid wax with lubricating properties equivalent to an oil obtained from the endangered sperm whale. Jojoba is under development in southern California, Arizona, Mexico, and many of the semiarid less developed countries (53). Mature jojoba plantations should yield over 1,000 kg/ha^{-1} at over $1 per kg. This yield could earn a gross return of over $1,000 per hectare.

Guayule (*Parthenium argentatum*) a plant native to the Chihuahuan deserts, contains natural rubber and is under extensive development by both the United States and Mexican governments (50). There is no reason guayule could not be cultivated in other semiarid regions of the world as a cash crop.

Hydrocarbon bearing plants such as *Euphorbia lathyris* have been suggested as raw materials for oil and gasoline production (7). The

drought-adapted legume trees *Acacia senegal* exudes a gum from wounds of the trunk known as gum arabic that has many industrial and food uses (18). Eighty-five percent of the world's annual supply of gum arabic, about 50,000 to 60,000 metric tons, is harvested and exported from the Sudan at prices of about $1 per kg (18). Other *Acacia* and legume trees, such as *Prosopis,* exude gums that could be developed for cash crops. Seeds of the fast-growing, drought-tolerant, annual sesame sell for $1 to $2 per kg and show potential for an arid zone cash crop (53). The fruits of the cactus *Opuntia ficus-indica* can produce dessert or table quality fruits. This author was served an excellent cactus fruit with a meal on a Chilean airline. Commercial (5 ha and larger) *Opuntia ficus-indica* orchards are currently operating in southern California to supply these fruits to supermarket chains. There are several little-known species of cactus that possess fruits equal or superior in quality to *Opuntia ficus-indica* that could also be developed (11). Because cactus use water very efficiently, they should support fruit and cash crop production in semiarid areas.

The pods of carob (*Ceratonia siliqua*) are broken into pieces, kibbled, and separated into seed and pod fractions. The pod fractions are sold for livestock food in Europe and are imported into the United States where they are manufactured into chocolate substitutes (34). Industrial quality gums are extracted from the seeds. In 1970, the world production of carob seed gum was 15,000 tons. Prices ranged from $0.62 to $1.10 per kg (43). The pods of *Parkia biglobosa* and *P. clappertoniana,* and a fermented product of the seeds known as dawadawa, are sold for human food on the subsistence levels in markets in Senegal and other parts of West Africa.

Research organizations: The most extensive germplasm collections, plantings, and cytogenetic studies of jojoba are being made at the University of California-Riverside under Dr. D. M. Yermanos. This has been funded by the United Nations Development Programme (UNDP), NSF, and the California State Legislature. Another large-scale jojoba research operation is being carried out at the University of Arizona under Dr. L. Hogan. There are numerous commercial jojoba developers, some of whom are less than scrupulous. Donor agencies should contact Yermanos or Hogan before dealing with private jojoba developers. Dr. Yermanos has also developed nonshattering sesame types and mechanical harvesting devices with UNDP support. The USDA has a multi-million-dollar budget to develop guayule in the Southwestern United States.

The Diamond Shamrock Co. is supporting a multi-million-dollar project at the University of Arizona Office of Arid Land Studies to develop potential of hydrocarbon producing plants such as *Euphorbia lathyris.*

The Canadian International Development Research Center (IDRC) is supporting a research program to develop gum arabic for West Africa through the "Eaux et Foret" in Dakar, Senegal. The University of Chapingo, Mexico, has a program to develop spineless cactus (52). Dr. Richard Felger at the Arizona/Sonora Desert Museum has identified numerous arid land crops with potential including several outstanding cactus varieties.

Production of Livestock Food and Forage

Areas of use: In Mexico, *Prosopis glandulosa* var. *glandulosa,* and *Prosopis laevigata* are harvested from wild trees and sold to wholesale dealers who incorporate it into livestock rations. In 1965, 40,000 tons of mesquite pods were sold in commercial operations in Mexico (29). Undoubtedly, many more pods were used or bartered locally that were never entered into the agricultural statistics. One thousand ha of *P. juliflora* has been established in the Peruvian coastal desert under partial irrigation. By providing 250 mm of irrigation the first year and 160 mm thereafter, pod production of 6 to 7 t/ha^{-1} have been obtained from the Peruvian plantings (39). In nearby Chile, 30-year-old *P. tamarugo* trees growing in the *Atacama* salt desert have produced 6,000 kg/ha^{-1} of leaves and pods that are used to support a sheep-raising industry (44). Twenty-

two thousand hectares of *P. tamarugo* have been planted by the Chilean corporation CORFO (54). Felker has visited these areas to assist CORFO with vegetative propagation, selection techniques, and nitrogen fixing inoculants.

In the Southwestern United States, mesquite pods were the staple for Indians in southern California and Arizona deserts (13), but today are only marginally important in supporting wildlife. In West and East Africa the pods of *A. albida* and *A. tortilis* are highly regarded as a supplemental livestock feed (12,34). Some *A. albida* pods are collected and stored for later rationing to cattle on a subsistence level, but no organized or commercial use of pods has been attempted (12). The forage of *Acacia xanthophlea* and *A. hockii* supplies much of the diet of giraffes in the Serengetti National Park in East Africa. Pellew (41) has suggested that the Acacia-giraffe ecosystem be managed for meat production.

Forage systems based around the spineless cactus (*Opuntia ficus-indica*) have been widely used in Mexico and North Africa where the spineless pads are fed to cattle. Selections of saltbush (*Atriplex* species) are high in protein and carotenoids and constitute a useful livestock forage. The Chilean corporation CORFO has planted thousands of hectares of saltbush in contour ridges along the Chilean coast for use as cattle food (Felker, personal observation). In Tunisia, commercial-scale, government-supported plantings of saltbush provide forage for grazing animals (22).

In Mexico, cattle rations have been formulated from high energy, sweet, highly palatable mesquite pods; high protein, high carotenoid and low palatability saltbush foliage; and high-energy containing cactus pads (29). These three plants possess the complimentary physiological characters of high salt tolerance in saltbush, high water to dry matter conversion efficiencies of cactus, and nitrogen fixing properties of mesquite.

Research organizations: Surprisingly little research is being done about these forage plants. The Tunisian and Chilean governments support the largest developments of forage-producing plants. The Chilean company CORFO has planted thousands of hectares of *Atriplex*. CORFO has investigated plant spacing, canopy closure, and pod productivity as a function of age for 36-year-old *Prosopis tamarugo* plantations (44). They are just beginning to become involved with selection work, nitrogen fixation, and vegetative propagation.

The Tunisian government has employed large earth-moving equipment and water transport vehicles to establish saltbush and cactus plantings (22). The Algerian government also has initiated some *Opuntia* plantings (33). Dr. Henri LeHouerou, formerly of the International Livestock Center (ILCA) in Addis Ababa, has been a key figure in North African developments of *Atriplex* and *Opuntia*. The Chapingo Agricultural Experiment Station outside of Mexico City has made selection of *Opuntia* with promising economic characters (52). Lopez, et al. (28), at the Antonio Narro Agricultural University in Saltillo, Mexico, has conducted a thorough analysis of the productivity and ecosystem characteristics of economically important aspects of *Opuntia* production in Mexico. The International Development Research Center, Ottawa, is supporting a *Prosopis juliflora* forage production project in Peru.

In the United States, Dr. C. M. McKell, Plant Resources, Inc., Salt Lake City, and Dr. J. Goodin of Texas Tech University have conducted extensive research on saltbush as an economically important forage crop. Felker, while at University of California-Riverside, made *Prosopis* selections for pod producing characteristics in cooperation with Becker and Saunders at the USDA Western Regional Research Center. They also have conducted proximate analyses and feeding trials on the pods.

Intercropping Traditional Food Staples With Arid Adapted Legumes To Sustain High Food Staple Yields

Areas of use: *Prosopis cineraria* has been widely used in the Indian-Pakistan region on a subsistence level to increase yields of pearl millet and other forage crops grown beneath its canopy (31). *Acacia albida* has been used

in West Africa to increase yields of millet, sorghum, and peanuts (9,8,12). Farmers in the 400 mm annual rainfall region of Senegal remarked to this author that *Parkia biglobosa* had the same fertilizing effect as *Acacia albida* on millet and sorghum.

Research organizations: The French overseas development organization ORSTOM commissioned soil fertility studies carried out by Dancette and Poulain (9) and Charreau and Vidal (8). AID commissioned a state-of-the-art report on *Acacia albida* in 1978 (12). FAO supported a nursery scheduled for termination in 1978 in Kebemer, Senegal, dedicated to raising enough *Acacia albida* seedlings to plant 1,000 ha per year at 45 trees per hectare. A CARE project in Chad was involved in reforestation with *Acacia albida*. No serious field study has ever been conducted to develop improved genetic stock and management practices for arid-adapted leguminous trees.

Slowing the Spread of Desertification in Arid Regions

Little work is being carried out to slow desertification. K. O. Khalifa, working for the Sudan Council of Churches, has planted 400 acres of *Prosopis* along irrigation canals to prevent the wind from filling them. The Indian government has been planting shelterbelts with *Prosopis* and other arid adapted trees since the 1920s and 1930s (25). No serious efforts employing arid-adapted shock, e.g., *Prosopis, Acacia,* or *Leucaena,* and modern forestry practices have been applied to control of desertification in less developed countries.

FERTILIZER, PESTICIDE, IRRIGATION, AND MACHINERY REQUIREMENTS

Irrigation Requirements

Over 90 percent of the land in semiarid regions must rely on rainfall without supplemental irrigation (excluding areas where water harvesting technologies are possible). All of the desert-adapted trees, shrubs, and ephemerals described here have the capability to grow without irrigation in semiarid zones. If water is not available, these plants can close stomates, shut down photosynthesis and transpiration, allow their finely divided leaflets to reach air temperature, and adjust their water potentials to minus 40 to 50 bars and wait for the next rain (17). Annuals would wilt and die under the same conditions.

Reasonable production from reproductive structures, such as mesquite pods, jojoba nuts, or cactus fruits cannot be expected below 250 mm annual rainfall unless they are located in water drainage areas or areas where water accumulates. Growth of vegetative parts for wood or forage production probably will continue from 150 to 250 mm annual rainfall. Deep-rooted tree and shrub systems are not as susceptible to moisture stress as are shallow-rooted annuals. To get optimal water use, an agroecosystem needs an optimal mix of nitrogen fixers and water to dry matter conversion specialists. When it is possible to use cactus, which has a fivefold greater efficiency of converting water to dry matter than legumes (17), legumes should not be used to produce the energy portion of livestock feed. However, legume leaf litter will be required to create good fertility so the cactus can achieve its maximum water use efficiency. For the same reason, cactus should not be used to produce the protein and nitrogen needs of livestock when it is possible to use legumes. Livestock need both energy and protein rations and both energy and protein producing plant specialists are required.

Fertilizer Requirements

A central component of this approach to developing country agriculture is widespread in-

corporation of arid-adapted, nitrogen fixing legumes that are capable of fixing nitrogen under conditions too harsh for temperate legumes (e.g., clover, alfalfa, etc.). These legumes require no nitrogen themselves and when properly incorporated into a diversified ecosystem, they will reduce nitrogen needs for non-legumes as well. Many of these plants, both leguminous (e.g., mesquite) and non-leguminous (e.g., jojoba) have very deep root systems (13) capable of mining nutrients found in clays, bedrock, and parent materials. Additionally, these deeper rooted shrubs would be expected to have a higher capture ratio of applied fertilizers because they are less likely to allow nutrients to leach beyond the deep root zone. Also, many of these plants are perennial, and they would be expected to reduce wind and water erosion.

Under rainfall as low as 300 mm, it may be desirable to practice clean cultivation or use herbicides between rows of mesquite, cactus, saltbush, jojoba, and guayule to increase water infiltration and to reduce water competition from grasses and forbs. Once established, the risk of wind and water erosion present with clean cultivation should be less than the similar risk with annual crops. Drought-hardy shrubs and trees should make more effective use of applied nutrients than water-stressed, herbaceous, annual crops.

If drought-adapted legumes are widely incorporated into managed arid ecosystems, phosphate and sulfate will ultimately become limiting and will have to be supplied. Both nutrients stimulate legume production and can be supplied in single superphosphate.

Pesticide Requirements

It is difficult to imagine how the plant ecosystems described here would be any more or less susceptible to insect or bird attack than any other ecosystem. Once established, perennial tree and shrub crops would survive competition from grasses and forbs without weed control measures. However, their productivity probably will be greatly enhanced if herbicides or cultivation were used to eliminate water competition from grasses and forbs. For the first few years of shrub and tree stand establishment, competition from grasses and forbs must be eliminated either by herbicides or cultivation.

Machinery Requirements

A variety of options employing varying degrees of mechanization are available to establish tree and shrub plantations. This author envisions that most plantations will employ containerized seedlings planted with a liter or two of water. This can be accomplished manually with dibbles or post-hole diggers or mechanically with an 80 hp tractor pulling a transplanter capable of planting 1,000 trees per hour. It may prove useful to establish a seedbed for seedling transplant with the same level of preparation given to annual crops. However, after the first year an annual deep cultivation as required for annual crops will not be necessary. Where fruits are to be harvested (e.g., jojoba, mesquite beans, etc.), light surface harrowing or disking will prove useful for weed control, to increase water infiltration, and to provide a clean surface to pick up the fallen fruits. Pruning of tree and shrub crops will be necessary to allow access for harvesting of fruits.

In biomass farming operations, where complete canopy closure is desired, annual cultivation would be unnecessary and impossible to carry out after canopy closure. An annual ground preparation and planting, carefully timed with arrival of rains to allow germination and full use of the rainy season, will not be necessary for the tree and shrub crops. Established annual and perennial crops will not face a labor shortage at planting time as do annual crops. The light cultivation that may be useful with tree and shrub crops can be performed on a much less rigid schedule when labor, draft animals, and machinery are available. If herbicides are available and acceptable, they can be used in lieu of light cultivation. Tree and shrub crops would require much lighter equipment than annual crops and the annual site preparation necessary for annuals could be avoided.

RESEARCH, DEVELOPMENT, AND IMPLEMENTATION OF ARID-ADAPTED PLANT ECOSYSTEM PRODUCTION TECHNOLOGIES

An outline of research required to develop these plants and cost estimates to do so are given in table 1. Research centers are proposed in six locations to collect and store germplasm, to plant germplasm nurseries, to reevaluate promising nursery selections in larger sized plots, to compare input/output resource ratios of different plant systems, to evaluate monoculture and polyculture arid-adapted systems, and to provide material and adminstrative support for the research.

The research program outlined in table 1 is appropriate for the first phase of the research. Extensive germplasm collections and plantings would be required once at a cost of approximately $1,500,000. A funding effort 15 percent of the initial level would be appropriate after initial collections and plantings were made. Funds used for collections and plantings in the first phase should be allocated to weed and insect control, cultural operations such as harvesting, pruning, and planting methods for nursery stock, and extension short courses during the second phase of the research.

Large genetically diverse germplasm collections and promising plant selections are available for some of the plants described here such as jojoba, guayule, and atriplex species. For other plants, germplasm collections and selections of promising lines will have to be made. The plants that require germplasm collection and selection and the methodology for accomplishing that is outlined below.

Seeds should be taken and maintained as single plant selections from *Acacia tortilis* and *A. seyal* in East Africa, from *A. albida* in East and West Africa, from *Parkia biglobosa* in West Africa, from *Prosopis cineraria* in the Mideast and India-Pakistan region, and from *P. alba, P. chilensis, P. tamarugo, P. pallida, P. articulata, P. tamarugo,* etc. in Argentina, Chile, Peru, Mexico, and Hawaii. Short, shrubby legumes of the genus *Dalea* should be collected in Southwestern United States, *Tephrosia* in Texan-Mexican area, and *Zornia* in Sahelian Africa. Cactus genera such as *Opuntia* and *Cereus* should be collected in Southwestern United States. During these collections, attempts should be made to collect for as much diversity as possible as well as to collect for economically desirable characteristics, e.g., heavy pod production, size and sweetness of fruit, large trees, presence of large amounts of leaf litter, and presence or absence of thorns. The plant should be collected over its entire geographical and ecological range.

All of the collections should be evaluated in uniform plantations with a minimum of four replicates of five trees per replicate. For the trees, height measurements should be performed the first year, stem diameter measurements for biomass estimation should be performed every year, and pod productivity measurements should continue indefinitely. One germplasm planting should be evaluated in a 300 and 500 to 600 mm annual rainfall regime in the India-Pakistan region, in East Africa, in West Africa, in the United States, and in South America. The purpose of the American planting would be to provide American researchers with biological research material and exposure to these different cropping systems. An additional site should be located near a seacoast to use seawater irrigation to screen for salt-tolerant germplasm.

The Hawaiian Niftal rhizobia collection should be evaluated for rhizobia for the legumes and techniques developed to ensure effective nodulation of field plantings. Soil samples from native stands might contain rhizobia with unique properties and should be used to inoculate native plants for comparative purposes.

Most *Acacias* (Sief-el-Din, 1980) and probably all *Prosopis* (47) are obligately outcrossed. As a result, trees will not breed true and seed and clonal propagation techniques will be required. Both tissue culture propagation and traditional rooting of cuttings should be examined. Rooting of stem cuttings is difficult for *Pro-*

Table 1.—Outline of Research Procedure

Level of support per year ($ 1,000)	
	1. Develop germplasm collections where none exist
	A. Collect single tree selections of leguminous trees over broad range for:
	1) pod production
	2) large size
	3) thorn characteristics
	4) leaf litter
	B. Collect following genera:
100	1) *Acacia tortilis* and *A. seyal* in East Africa
100	2) *Acacia albida* in East and West Africa
100	3) *Parkia biglobosa* in West Africa
100	4) *Prosopis cineraria* in Indian-Pakistan region
200	5) *Prosopis alba, P. articulata, P. chilensis, P. nigra,* and *P. tamarugo* in Mexico, Hawaii, Southwestern United States, Argentina, Chile, and Peru
100	6) Make cactus collections in Southwestern United States and Mexico
100	7) Short, shrubby legumes, *Dalea* in Southwestern United States, *Tephrosia* in deep South, and *Zornia* in Sahelian Africa
	2. Obtain good selection of following arid crops already subjected to germplasm collection and screening:
25	A. Jojoba—Drs. Yermanos and Hogan
	B. Guayule--USDA
	C. Euphorbia—Dr. Calvin
	D. Atriplex—Drs. McKell and Goodin
	E. Leucaena—Dr. Brewbaker
	3. Plant out four replicates of five trees (plants) of all accessions for germplasm nursery at a 300 mm and 500-600mm annual rainfall regime in:
100	A. East Africa, e.g., Sudan
100	B. West Africa—Senegal
100	C. India-Pakistan region
100	D. South America
100	E. Southwestern United States
100	F. Site along coast to irrigate with seawater for salinity trials
60	4. Evaluate Niftal collection of rhizobia suitable for tree legumes. Develop techniques to insure effective nodulation.
100	5. Conduct protein, sugar, fiber, and toxicity analyses on pods that are produced.
120	6. Develop clonal propagation techniques at central facility:
	A. Rooting of cuttings
	B. Via tissue culture
450	7. Evaluate germplasm nursery for:
(6 sites × 75)	A. Height measurements first year
	B. Stem diameter measurements yearly
	C. Pod production and/or pod chemical characters
	D. Make clones of outstanding single trees
1,200	8. Evaluate clonal outstanding material in replicated 0.1 ha minimum-sized plots.
(200 × 6 sites)	
180	9. Multiply and distribute best selections to interested individuals and organizations.
(30 × 6 sites)	
1,200	10. Evaluate comparative advantages of selections developed above in mono- and poly-culture with *Opuntia,* jojoba, guayule, atriplex, etc.
(200 × 6 sites)	
400	11. Evaluate large N fixing trees with staple cereal crops in field plantings.
(200 × 2 sites)	
600	12. Evaluate short N fixers with jojoba, guayule, saltbush, etc.
(200 × 3 sites)	
5,735	**Total direct research**
4,265	Support facilities, travel, secretarial, library, statistical analyses, computer services, etc.
	Grand total

sopis. To achieve success for large-scale plantings, a thorough evaluation of rooting methods including evaluation of mist, atomized fogging, and tent humidification devices, screening trials of hormone mixtures, evaluation of out-of-doors and greenhouse grown stock, and use of growth chambers to determine optimal light, temperature and humidity level for cuttings will be required.

Most annual legumes are highly self-fertile and breed true to type. These selections will not require vegetative propagation, but germplasm multiplication areas will be required. Laboratory analysis of crude protein, sugar, and fiber should be conducted on pods, fruit or other economically important plant structure.

Single tree selections should be made from the germplasm nursery on the basis of: 1) height and biomass determinations, 2) pod production and pod chemical characters, 3) presence or absence of thorns, and 4) other characteristics deemed important. These selections should be clonally multiplied and reevaluated with four replicates of 0.1 ha minimum sized plots per selection. Sufficient quantities of the clonally multiplied material should be made to allow distribution to requesting individuals and organizations.

Once reasonably productive selections of the leguminous trees and cactus have been developed, they should be compared with advanced strains of jojoba available from Yermanos and Hogan, from guayule available from USDA, and from saltbush available from McKell and others. The comparative advantages and relative resource requirements for these crops should then be evaluated as monocultures and polycultures. The large nitrogen fixing trees *P. cineraria* and *A. albida* should be evaluated in various spatial configurations with the staple crops millet, sorghum, and peanuts. The short shrubby and herbaceous legumes of the genera *Tephrosia, Zornia,* and *Dalea* should be evaluated with jojoba, guayule, saltbush, and opuntia.

As with all crops, solutions to weed problems, insect problems, and cultural practices will have to be developed for these ecosystems. Herbicide and cultivation methods should be examined for weed control and insecticide, biocontrol, and integrated pest management should be evaluated for insect control. Harvesting, pruning, plant spacing, and planting methods also require development.

It has been the experience of Dr. Yermanos with jojoba and of this author with mesquite that once genetically superior strains have been produced the demand for the strains and the technology associated with them will greatly outstrip the supply. Elderly ladies with 100 square feet of desert in their backyard in Yucca Valley, California, business executives, and ministers of agriculture in arid developing countries will ask the project leader to visit their backyard or country to set up the appropriate technology. It is imperative to develop sufficient plant material for further multiplication and to train extension personnel to help farmers, businessmen, or government leaders use the technology. Short extension courses provided by staff involved in germplasm nurseries and evaluation centers would be an ideal method of disseminating the information.

The staff of the germplasm nursery and evaluation centers would require a Ph.D. project leader for: 1) *Acacia tortilis* and *A. seyal,* 2) *Acacia albida,* 3) *Prosopis cineraria,* 4) *Parkia bioglobosa,* 5) the American *Prosopis* species, 6) the shrubby and herbaceous legumes, 7) the cactus, 8) the atriplex complex, 9) guayule, 10) jojoba, and 11) other overlooked species. A central tissue culture and clonal propagation center should develop the techniques for clonal propagation and have at least two Ph.D.'s, six B.S.'s and/or master's level technicians and six to eight support personnel preparing media, washing dishes, etc. Each research center should have two B.S. or M.S. full-time personnel and six nonskilled laborers rooting cuttings and/or multiplying germplasm for research and/or further distribution. The availability of a statistician and computer for analysis of field experiments is essential.

A major effort will be required to develop support facilities for research in arid develop-

ing countries of Africa. Telephone service, mail service, ground transportation, and freight services to and from Europe are too unreliable to make effective research possible in East Africa and perhaps other countries. It is absolutely essential that the plant research be conducted in the climate and on the soils where it is to be used and this requires development of support services for the research.

CONSTRAINTS FACING DEVELOPMENT AND IMPLEMENTATION OF ARID-ADAPTED PLANT PRODUCTION TECHNOLOGIES

There are no major or theoretical scientific constraints on using these technologies, but applied research efforts are required in several areas. Techniques need to be developed for clonal propagation of the species described here—both rooting of cuttings and tissue culture. Planting techniques, greenhouse and field cultural practices need to be optimized. A continued effort to identify and propagate better genetic selections is required.

Environmental constraints to development of these systems are minimal, as increased vegetation in arid developing countries has the effect of halting desertification. There are, however, serious cultural constraints to development of perennial production systems. For instance, in Sahelian Africa the perennial vegetation is viewed as community-owned (48). Thus, the pods or fruits from trees can be taken by anyone, even if the trees are on privately owned land.

Similarly, people can cut branches from nonprotected species of trees for fuelwood even if the landowner planted the trees for his own fuelwood use. Freely roaming goats that eat young seedlings constitute a major problem in establishing perennial production systems. Control of the movement of goats is probably an insoluble cultural problem and thus goat-proof devices to protect young seedlings will have to be devised.

Political constraints on the development of these technologies stem from politicians' and bureaucrats' unfamiliarity with use of these perennial crops. This is most accurately described in Pelissier's explanation of why *Acacia albida* is not more widely used in West Africa (14).

> One cannot help but be astonished that an agronomic research center established to study the Serer people (in Senegal, West Africa) is not more interested in the methods and effectiveness of native farming systems. These researchers ignore the milieu of naturally-regenerating *Acacia* stands by which they are surrounded. This mark of indifference and incomprehension for African techniques is too often manifest by European specialists or those trained in Europe. In order to promote their own cultural values, these researchers use the terms "modern" and "scientific" as if laboratory and field techniques are completely inapplicable, for social or economic reasons, to the truly native farming systems.
>
> *Acacia albida* suffers from the division of the technical services. The agronomist regards the presence of the tree in the field as an adversary to be eliminated. The forester is not interested in the tree because *Acacia albida* does not grow in what could be termed a forest and is, therefore, not capable of being dealt with by standard silviculture concepts. The role of *Acacia albida*, including its growth and germination conditions, illustrates its marvelous character which cannot be dissociated from its genuine agricultural setting and illustrates the necessity for deep-seated action to aid the farming population. At this time in our intimate knowledge of political techniques for rural management, an end must be placed to the absurd division of agriculturally related disciplines which enclosures agricultural development specialists. It is not lack of concern in the development specialists that causes this problem but rather their overspecialized training, and above all the administrative structures that thwart their action and hinder an integrated development plan which alone can be effective.

EFFECT OF TECHNOLOGY IMPLEMENTATION ON CAPITAL, LABOR, AND LAND REQUIREMENTS

The initial inputs required for the systems described in this paper are low but the output/input ratio of the system is high. Yield increases will tend to stimulate more investment in the technology. For example, assume a farmer will plant 1 ha with 200 *Prosopis* trees. The wholesale seedling cost should be approximately $0.15, requiring an outlay of $30. These seedlings could be planted on his own land with only a shovel, and some buckets for watering the seedlings after transplant. If planted in regions at 500 mm annual rainfall, at year 10 the tree should be producing 4,000 kg of pods per hectare (16). These pods typically have protein and nitrogen contents of 12.5 percent and 2.0 percent, respectively (4). Thus, the pods contain 80 kg of N, which is worth $40 at today's price of $50 per 100 kg of N. To achieve capture of 80 kg of N in pods from chemical fertilization, at least double the amount of nitrogen in the pods, or 160 kg of N, would have had to have been applied. Thus, the cost to provide the nitrogen found in the pods would have been $80 per year. Recalling that the farmer's cash outlay for seedlings was $30, his annual return on the seedling investment from nitrogen alone is 270 percent. His $30 investment in seedlings probably would be returned from 60 kg of N fixed by the plants in 2 to 3 years.

Because most of these trees are outcrossed and planted only once every 30 to 50 years, it would be most advantageous to plant clonal material from outstanding individual trees. Thus, commercial tree nurseries would be required to supply young trees to villages in the countryside. Hopefully, farmers would recognize the importance of obtaining high quality, clonally propagated seedlings for long-term plantings, and would support commercial village level nurseries that would deliver superior genetic stock to the local population.

Fertilizers other than nitrogen would be required. Phosphate and, to a lesser extent, sulfate fertilizers stimulate nitrogen fixation in legumes and would be a worthwhile investment. Phosphate fertilizers have approximately the same unit price as nitrogen fertilizers but only 10 percent as much phosphate is required. Annual crops such as maize may capture only 40 to 50 percent of applied fertilizer partially because of leaching beyond the root zone (37). Shrubs and trees such as *Acacia*, *Prosopis*, and jojoba commonly root to 10 meters (13) and would achieve higher capture ratios of applied fertilizer.

There is no reason to suspect that any more or less pesticides would be required than in other kinds of systems since insects would be just as likely to attack tree or shrub crops as annual crops. Due to the low till or no tillage requirement for many of these shrub and tree-based production systems, agricultural machinery requirements would be expected to be less than those of conventional plant production systems. Most harvesting in arid developing countries is done by hand. With increased yields of traditional crops stimulated by association with leguminous companion crops, the demand for labor at harvesting time will increase. Production of large quantities of tree legume pods, jojoba nuts, and fuelwood will also increase the labor demand for harvesting operations.

The low requirements for tillage machinery and the lack of a nitrogen fertilizer requirement will greatly reduce credit requirements for these two traditionally high credit requiring areas. On the other hand, the several years' wait prior to harvest of perennial crops will require credit to pay for the seedling costs.

IMPACT OF WIDE-SCALE TECHNOLOGY IMPLEMENTATION ON THE SOCIOECONOMIC STRUCTURE OF AGRICULTURE IN DEVELOPING COUNTRIES

Most of the plant systems (technologies) discussed in this report are widely used by subsistence farmers in the developing countries. The plants used are primarily volunteer seedlings of unselected genetic stock that the farmers may prune and care for (40). This system is comparable to use of unselected races of maize and wheat as would have been done in the late 1800s in the United States and Europe. Placing these widely used, but scientifically unmanipulated plants into a research and development framework will probably yield increases similar to that achieved by first inbred and then hybrid lines of maize and other cereals.

Vigorous, naturally occurring tree legume hybrids have been observed and clonally propagated by this author and demonstrate the ease with which hybrids can be formed. Maize yields increased from less than 20 bushels per acre in the early 1900s to close to 100 bushels per acre at present. The plant systems described here probably have the potential of achieving the same yield increases. Perhaps a two- to three-fold increase in plant productivity can be expected in 5 to 15 years and a five- to ten-fold increase in 50 to 100 years. Unlike maize, these systems are based around nitrogen-fixers and will not require fossil-fuel-derived and energy-intensive nitrogen fertilizers.

Assuming these kinds of yield increases in tree legume pod production, fuelwood production, cash crop production, soil fertility, and ensuing staple food production, returns to farmers can be expected to increase in the same approximate fashion As the farmers income rises, his demands for goods and services will rise and stimulate the economy as a whole. A greater tax base will then be available to support more roads, schools, and health services, which will in turn decrease unemployment.

The economy of a country with an agrarian society is inextricably tied to the primary productivity of the ecosystem. As long as substantial progress is being made toward achieving the economic goals of the rural population, there will be fewer economic grounds fostering political instability. Past efforts to stabilize the political systems of arid developing countries, such as Iran, with military hardware systems have proven futile. It is imperative to develop plant systems that have the capability to directly impact the smallest farmers on the local level to increase his well-being and decrease economically fostered political unrest.

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Work Statement

Topic

Development of low energy input technologies to increase and stabilize productivity of agricultural ecosystems in dry regions of less developed countries.The contractor shall:

1. Describe how the technologies operate and what beneficial or adverse impacts they have or might have on enhancing the sustained production of food and forage from tropical and subtropical soils.
2. Describe where the technologies are being used. Describe whether each technology is being used on a commercial level, a subsistence level, as a pilot program, or is being applied only in the research state. Describe who is conducting the major research on the technology. Describe what organizations (AID, FAO, and others using U.S. funds) are funding development of the technology and what organizations are implementing it on a project scale.
3. Explain in some technical detail how these technologies increase or decrease the need for fertilizers, pesticides, irrigation, and machinery when applied to tropical/subtropical soils.
4. Discuss the potential role of these technologies being used to restore, improve, or sustain in perpetuity the food and forage productivity of tropical and subtropical soils, and the likelihood that they will be used widely.

We appreciate that the author may not be a specialist in economics or sociology; however, his experience and insights on the following questions are still of interest to OTA, especially as they relate to lesser developed countries. Therefore the contractor shall:

5. Describe a plausible research, development, and implementation scenario in which these technologies realize their potential in enhancing productivity of tropical soils. What organizations would be involved? What levels of capital and trained personnel would be necessary? What degree of attitudinal changes would be necessary for consumers, farmers, government agricultural experts, bureaucrats, politicians, foreign advisors, policymakers in foreign aid or lending institutions, etc.? What biophysical (soils, climate, topography), cultural, and socioeconomic conditions would be most conducive to successful implementation of the technology? Where do these conditions exist or where are they likely to develop? To indicate the priority of the various steps that need to be taken on this technology, contractor shall discuss how he (if he were the head of a wealthy foundation) would spend $10 million on research, development, or implementation of the technology.
6. Describe the major scientific, environmental, cultural, economic, and political constraints on development and implementation of these technologies.
7. Describe how implementation of these technologies would affect the need, in the region where they were implemented, for inputs of capital (agricultural chemicals, machinery, credit, seed, and other materials from the implemention farm), labor, and land.
8. Describe what the impact of wide-scale implementation of these technologies would be on the socioeconomic structure of agriculture in the implementing regions. For example, does the technological implementation give rise to economies of scale, or diseconomies of scale, that would make large or small farm units more competitive? How would the technologies either displace or create demand for farm laborers.

Deliveries

The contractor shall deliver to OTA the original copy (not a reproduction) of the typewritten 25- to 35-page report, acceptable to OTA, with abstract and literature citations, by November 24, 1980.

Chapter VII

Azolla, A Low Cost Aquatic Green Manure for Agricultural Crops

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Contents

	Page
Introduction	107
What Is Azolla?	107
What Are the Benefits of Using Azolla?	109
The Present Status of Azolla	111
Where Azolla Is Being Used in Agriculture	111
How Azolla Is Used as a Green Manure	112
Who Is Doing Azolla Research?	114
What Organizations Are Financing Azolla Research?	114
Azolla's Effect on the Need for Agricultural Inputs	115
Fertilizers	115
Pesticides	115
Irrigation	115
Machinery	116
The Potential Use of Azolla	116
How Does Azolla Affect the Productivity of Tropical Soils?	116
The Potential Use of Azolla	116
A Research, Development, and Implementation Program	117
The Program Elements	117
What Organizations Should Be Involved?	118
What Is the Necessary Level of Financial Support?	118
What Are the Personnel Requirements?	119
What Are the Attitudes of Those Who Would Be Affected?	119
What Are Conducive Conditions for Implementation of the Technology?	119
Where Do Conducive Conditions Exist and Where Are They Likely to Develop?	120
What Is the Sequence of Steps Leading to Successful Implementation?	120
Constraints on the Development and Implementation of Azolla Technology	120
Scientific Constraints	120
Environmental Constraints	120
Cultural and Economic Constraints	121
Political Constraints	121
The Effect of the Implementation of Azolla Technology on the Need for Inputs	122
Capital	122
Farm Labor	122
Land	123
Conclusions	123
References	124

Figures

Figure No.	*Page*
1. Azolla	108
2. Azolla as Food and Fodder	110
3. Geographic Distribution of Azolla	111
4. Incorporating Azolla Into Soil	113

Chapter VII

Azolla, A Low Cost Aquatic Green Manure for Agricultural Crops

INTRODUCTION

The air we breathe is 79 percent nitrogen. Plants need nitrogen to make the proteins that allow them to harvest sunlight and carry on natural processes. Unfortunately, nitrogen in the air is in an inert N_2 form that cannot be used by plants. Only two kinds of organisms have the ability to convert inert atmospheric nitrogen to a usable form such as ammonia. These two organisms are blue-green alga (cyanobacteria) and certain species of bacteria. *Rhizobium* bacteria are the nitrogen-fixing partners of the well-known legume/*Rhizobium* symbiosis of soybeans, alfalfa, etc. The blue-green alga *anabaena* are the nitrogen-fixing partners of the virtually unknown *Azolla/Anabaena* symbiosis.

Until this century, nitrogen-fixing bacteria and blue-green alga, existing under freeliving or symbiotic conditions, produced most of the new nitrogen entering the cropping system. Almost all farmers had to include legumes in their crop rotation in order to maintain soil fertility. This traditional practice continued until the discovery of fossil-fuel-dependent methods of producing nitrogen fertilizer that radically changed the economics of agriculture. The use of legumes in crop rotation was soon considered to be too expensive and troublesome and fell into disuse, except when grown as a cash crop. The change was most apparent in developed countries and in developing countries that adopted the "green-revolution" technology.

However, during the 1970s this change began to reverse itself. The rapidly rising price of fossil fuel-dependent nitrogen fertilizers caused the economics of agriculture to shift again. Rising prices are causing researchers to seek alternative methods for producing synthetic fertilizer and causing farmers to reconsider traditional methods for maintaining soil fertility.

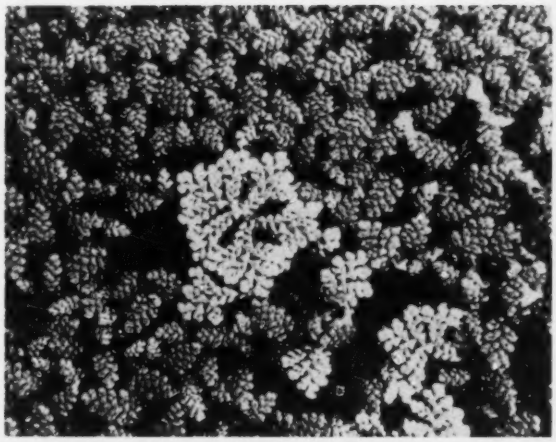
The traditional legume crops are and will continue to be the most commonly used nitrogen-fixing green manures, especially for upland crops. However, they have certain weaknesses for rice farmers. One of these weaknesses is that rice is traditionally grown on the most fertile and, consequently, intensively managed land. Rice farmers are reluctant to use part of the valuable growing season on a relatively slow-growing, legume green manure crop. Another problem is that many rice paddies are flooded or waterlogged, particularly during the potentially productive early part of the rice season when most of the transplanted rice is still in the nursery beds. Unfortunately, under waterlogged or flooded conditions most legumes cannot grow or fix nitrogen, so usually the paddy fields stand idle for a month or more while the rice seedlings mature in the nursery beds. The fast-growing aquatic Azolla has neither of these two weaknesses.

What Is Azolla?

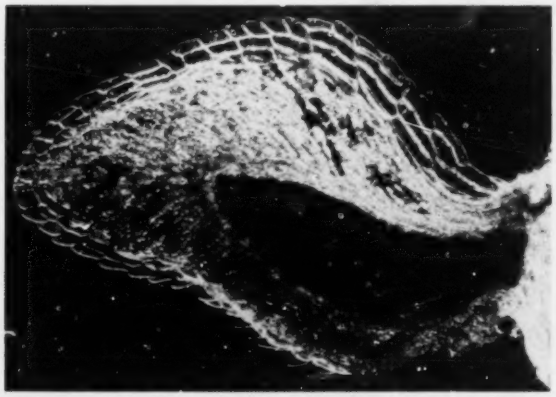
Azolla is a genus of small aquatic ferns that are native to Asia, Africa, and the Americas (figure 1). Three *Azolla* species are native to parts of the United States. They live naturally in lakes, swamps, streams, and other bodies of water. Some have been spread by man or natural means to various parts of the world. Some are strictly tropical or subtropical in nature, while others grow and thrive in either temperate or tropical climates. Azolla has been of interest to botanists and agriculturists for years because of its symbiotic relationship with a nitrogen-fixing, blue-green alga, *Anabaena*.

Figure 1.—Azolla

Azolla is a delicate aquatic fern that can be used as a green manure for rice and other paddy crops. It can even be grown as an intercrop with the paddy crop. When the azolla dies, it becomes fertilizer for the rice.



Most azolla species are only a few centimeters in diameter and each leaf is only a few millimeters long. Azolla can double its weight every 3-5 days and provide enough organic manure for a high yielding crop of rice.



There is a dark green cavity in the center of every azolla leaf which is inhabited by a species of blue-green algae. The algae takes nitrogen from the air and makes nitrogen fertilizer for the azolla.

Cells of the nitrogen-fixing blue-green algae, *Anabaena*, look like a string of beads. The larger egg-shaped cells specialize in producing nitrogren fertilizer while the more numerous smaller cells harvest sunlight.

Recently it has come under scrutiny as a green manure for flooded crops, particularly rice, since it is already used in rice in China and Vietnam.

The *Azolla/Anabaena* Relationship

The most remarkable feature of azolla is its symbiotic relationship with the blue-green alga, *Anabaena azollae*. The delicate fern provides nutrients and a protective leaf cavity for the *Anabaena*, which in turn provides nitrogen for the fern. Under suitable field conditions, the fern/alga combination can double in weight every 3 to 5 days and fix atmospheric nitrogen at a rate exceeding that of the legume/*Rhizobium* symbiotic relationship. Azolla can accumulate up to 2 to 4 kilograms of nitrogen/

ha/day (equivalent to 10 to 20 kg of ammonium sulfate), and since the *Azolla/Anabaena* combination grows in aquatic conditions, it can provide a potential nitrogen source for flooded crops such as rice. The exploitation of this potential is a challenge to agricultural scientists.

What Are the Benefits of Using Azolla?

Producing Nitrogen Fertilizer for Increasing Crop Yields

Azolla plants are described by the Chinese and Vietnamese as being miniature nitrogen fertilizer factories. Indeed the Vietnamese call them indestructible fertilizer factories, since azolla continued to produce nitrogen fertilizer for Vietnamese rice paddies even during the height of the Vietnam war.

The nitrogen fertilizer fixed by azolla becomes available to the rice after the azolla mat is incorporated into the soil and its nitrogen begins to be released through decomposition. In 25 to 35 days azolla can easily fix enough nitrogen for a 4 to 6 ton/ha rice crop during the rainy season, or a 5 to 8 ton/ha crop under irrigation during the dry season.

Maintaining Soil Fertility

As a green manure, azolla's influence on soil fertility is due to its organic matter and nitrogen. A humus compound is formed as a result of the incorporation and decomposition of azolla. Humus increases the water holding capacity of soil and promotes aeration, drainage, and the aggregation essential for highly productive soils. Organic matter can bind together soil particles and makes clayey soils more friable.

In addition to its influence on soil physical properties, azolla is important in the cycling of nutrients. While azolla is growing in the paddy, it fixes nitrogen and also absorbs nutrients out of the water that might otherwise be washed away. When the azolla is incorporated into the soil and humus is formed, these nutrients are slowly released into the soil as decomposition progresses.

Even though azolla appears to be a rather delicate plant that would rapidly decompose, it actually takes six weeks or more for most of the nutrients to be released because the plant has a rather high lignin content. Slow decomposition gives a natural slow release effect that is ideal for efficient absorption of the nutrients released. Another factor in azolla effectiveness as a green manure is its low carbon to nitrogen ratio of about 10:1. This high ratio ensures that azolla nitrogen will not be tied up by bacteria that are involved in decomposition of an over abundance of carbonaceous plant residues.

Producing Fodder for Pigs, Ducks, and Fish

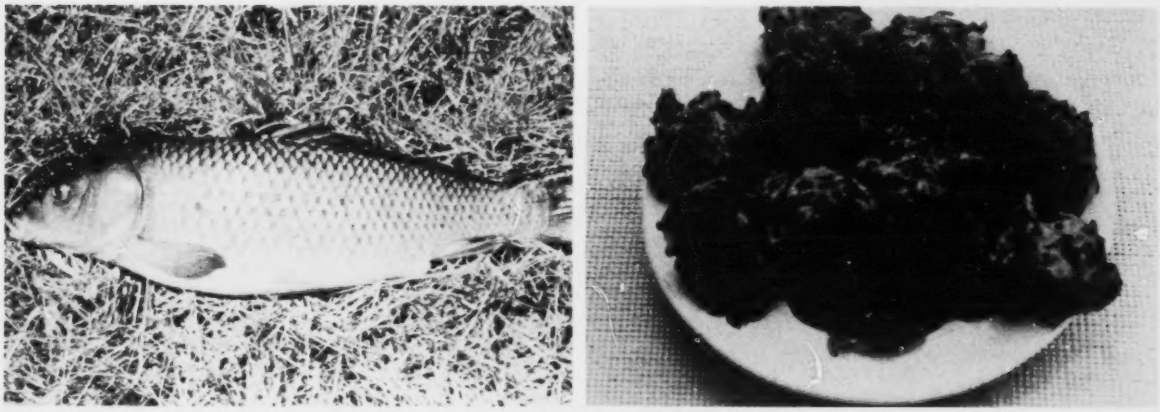
Azolla has traditionally been used as a fodder throughout Asia and parts of Africa. It is fed to pigs, ducks, and fish (figure 2). The grass carp (*Ctenopharyngodon idella*), Israeli Carp (*Cyrinus carpis*), and *Tilapia mossambica* prefer azolla over most other aquatic weeds as a source of food. Small lots of azolla growing in canals and ponds as food for pigs and ducks are ubiquitous throughout southern China. Azolla as a fodder probably has a longer history than as a green manure. There may even be potential for direct consumption by man. In India, women make a tasty deep fried dish of azolla mixed with batter (7).

On a dry weight basis, azolla has a protein content between 13 to 24 percent. One hectare of azolla can produce 1 to 2 tons of fodder per hectare per day, equivalent to 10 to 30 kg of protein per day. When these statistics are considered, azolla has a tremendous potential as a fodder crop in developing countries and also in the United States.

Recent work in India at G. B. Pant University indicates that azolla may be useful as a fodder for cattle. In trials there, growing heifers gained 0.33 kg/day when fed 0.9 kg of dried azolla with 2.1 kg of a 2:1 ratio of dry wheat straw and sugarcane tops. Control animals that were fed the same amount of wheat straw and sugarcane tops, but also received 1.5 kg of a concentrate feed, gained only 0.14 kg/day (1).

Figure 2.—Azolla as Food and Fodder

Although azolla is most commonly used as an organic fertilizer for rice, it can also be used as a fodder for pigs (left), duck (center) and fish and as a compost (right) for upland crops. Many of the pigs which are grown to produce China's famous Jinhua hams are fed on a diet which includes azolla.



Azolla is a preferred forage for many species of herbivorous fish. Azolla may also have potential for direct consumption by man if attractive uses can be developed. The photo on the right shows a deep fried dish of azolla mixed with batter.

Suppressing the Growth of Aquatic Weeds

Agricultural economists have estimated that Asian farmers, particularly women, spend more time weeding than on any other activity required for rice production. Although research is insufficient, it is commonly believed that azolla suppresses the growth of certain aquatic weeds. Weed growth is suppressed when azolla forms a thick, virtually light-proof mat. There are probably two mechanisms for this suppression, the most effective being the light-starvation of young weed seedlings by the blockage of sunlight. The other is the physical resistance to weed seedling emergence created by a heavy, interlocking azolla mat. In some weed-infested rice fields, the benefit from azolla weed suppression may even surpass its benefit as a nitrogen source. Rice seedlings are not affected by azolla's weed suppression effect because, when transplanted, they stand above the azolla mat.

THE PRESENT STATUS OF AZOLLA

Where Azolla Is Being Used in Agriculture

Azolla is already being grown commercially in China and Vietnam, where its usefulness has been known for years. Once restricted in use because of propagation problems, the fern is now being used in larger crop areas (figure 3).

Chinese use of azolla goes back hundreds of years, at least to the Ming dynasty. Its use in Vietnam dates to the 11th century. These two are the only countries with a long history of azolla cultivation. The practice probably began with recognition that the spontaneous growth of wild azolla in rice fields had a beneficial effect on the crop. Organized use of the fern could not occur, however, until reliable methods were developed to overwinter and oversummer the fern. Since azolla can only be grown from vegetative material, it must be protected during seasons that are too severe for its survival.

The original sites of azolla cultivation are thought to have been Zhejiang Province in China and Thai Binh Province in Vietnam. Until recently certain villages in these places had temples dedicated to the mythological discoverers of azolla. At the end of the 19th century azolla was being cultivated at favorable sites along the east Asian Coast as far south as 20° N latitude on the Red River delta in Vietnam and northeastward through Guangdong and Fujian Provinces to Wenzhou District near 28° N latitude in Zhejiang Province, China.

A major push for expanding the use of azolla began in China and Vietnam in the early 1960s. Before that time it was common for certain families or villages that had mastered the intricate techniques of oversummering and over-

Figure 3.—Geographic Distribution of Azolla

Distribution of *Azolla* species throughout the world. This distribution map is rapidly becoming outdated because many azolla species and varieties are being moved about and introduced into new places as research on azolla grows.

wintering azolla to control the supply of azolla-starter-stocks in the spring. Peasants had to travel to these villages to purchase their spring plants.

After the revolutions in China and Vietnam, the new governments eventually recognized the worth of azolla and began officially promoting its use and organizing the construction of propagation centers.

During colonial days in Vietnam, French scientists reported on the use of azolla and did some preliminary research, but its cultivation was never promoted officially. At the end of the colonial period, azolla was grown on about 40,000 hectares[1] as a green manure during the winter for the spring rice crop. In 1958, the new government established an azolla research center at the Crop Production Research Institute and set up an extension network with over 1,000 inoculum production bases to stimulate use.

Despite this promising beginning, the big push in azolla research did not come until the early 1960s. Articles on azolla began appearing in 1962, culminating in several articles and a large book (9).

Since the introduction of high yielding rice varieties to Vietnam in the early 1960s, most azolla has been grown as a monocrop before the spring rice. The cultivated area reportedly doubled from 1965 to about 700,000 hectares in 1978. As in China, azolla cultivation in Vietnam is seldom practiced in summer because the *A. pinnata* var. *imbricata* native to the Asian continent is sensitive to high temperatures and insects.

Vietnamese scientists have collected over 30 varieties of local azolla and have selected superior strains for heat, cold, salt, and acid tolerances. Despite these advances, reportedly most communes and cooperatives have not adopted these improved azolla varieties.

The Chinese story is much the same as that of Vietnam, although much more was known of the Vietnamese experience because of the availability of publications in English and French as well as in Vietnamese. Recently, information from China has become available (3,4,11,2,5).

Today, azolla is grown as a green manure on about 1.3 million hectares of rice in China. Research and development activities have increased significantly, as have extension activities to promote its use. Large posters have been produced to inform the public of azolla's usefulness and of its management requirements.

How Azolla Is Used as a Green Manure

Azolla can be used as a green manure (figure 4):

- by growing it as a monocrop and then incorporating it as a basal manure before the rice is transplanted; or transported to another site for use on upland crops;
- growing it as an intercrop and incorporating it as a top dressing manure after the rice is transplanted; or
- by growing it both as a monocrop and an intercrop.

All three systems can be successful but, as is common in agriculture, use of the green manure crop requires some adjustments in management of both the green manure and the main crop.

Monocrop Azolla is used in China and Vietnam during winter and spring to produce nitrogen for the spring rice crop. The same technique is used to produce nitrogen for the early summer rice crop, but this is less common since the growth of *Azolla pinnata* is affected by high temperature and heavy pest attack during mid to late summer.

Intercropped Azolla is usually grown with the rice in places where there is no time available in the cropping system for the monocropping of azolla. As an intercrop azolla will be initially incorporated by hand or rotary rice weeder and then later killed by heavy shading and/or high temperatures—with subsequent decomposition and release of nitrogen to the crop—at the stage of maximum rice tillering.

[1] 1 hectare = 2.47 acres.

Figure 4.—Incorporating Azolla Into Soil

Two of several methods for soils incorporating a monocrop of azolla as a basal green manure for rice. Both photos were taken during the spring of 1980 in Guangdong province, China. The photo on the left is *A. filiculoides*, the photo on the right is *Azolla imbricata*.

图 36 用痒推赶痒

图 37 用竹竿赶痒

The photo on the left shows an azolla beater being used to spread inoculum azolla after it was introduced into the field of a second later summer rice crop to grow with the rice as an intercrop.

The top center photo shows an azolla pusher which is used to spread inoculum azolla if it is applied to a rice crop after the rice is transplanted, or is used to concentrate and collect azolla in a nursery. The bottom center photo shows a bamboo pole being used to collect azolla growing in a canal.

Growing both monocrop and intercropped Azolla is a technique that is designed to use the growing period for azolla before the planting of the rice crop, *plus* production of added nitrogen for the crop through cultivation of intercropped azolla. In this system two different varieties of azolla may be used in each of the different periods. Different temperature and light sensitivities of azolla varieties make this possible.

Who Is Doing Azolla Research?

A number of centers are conducting azolla research. Most of this work is less than 5 years old. Both China and Vietnam are studying *Azolla pinnata* var. *imbricata* under their own conditions. Recently, the Zhejiang Academy of Agricultural Sciences has had an opportunity to evaluate the other *Azolla* species (*caroliniana, filiculoides, mexicana, microphyhlla,* and *nilotica*) for use in China.

Many developing country rice research centers have begun azolla research, but with little success to date. Probably the most successful program is in Thailand, where the Ministry of Agriculture has been sponsoring an azolla program that has progressed through the regional extension stations and has now reached the stage of demonstration plots in the fields of progressive farmers.

The International Rice Research Institute started an azolla research program nearly 8 years ago (10). IRRI is studying the use of several azolla species for use in flooded rice.

There are three major centers of azolla research in the United States. One is the University of Hawaii, where agronomic and physiology studies are underway to characterize and understand the usefulness of all azolla species in tropical crop production systems, including rice and taro (5). The work is led by T. A. Lumpkin who was selected by the National Academy of Sciences to conduct research on azolla in the People's Republic of China in 1979 and 1980 at its foremost azolla research center, the Zhejiang Academy of Agricultural Sciences at Hangzhou.

Studying azolla management to fit temperate, broadcast-sown production systems is the focus of the research program at the University of California at Davis (8). Research objectives at UCD include use of *A. filiculoides* as a monocrop basal green manure crop for springsown rice and *A. mexicana* as an intercrop in rice. The UCD program received a grant from the USDA Competitive Grants Program in 1980 and a grant from the National Science Foundation.

Basic physiology studies are the focus of the program at the Kettering Laboratory focused on understanding the *Azolla/Anabaena* relationship (6). The program has been supported by a grant from the National Science Foundation and a grant in 1979 from the USDA Competitive Grants Program.

Another azolla research program that we know less about is at Virginia Commonwealth University, where the isolation and reconstitution of the *Azolla/Anabaena* association are being studied. This work has been supported by a grant from the USDA Competitive Grants Program; the first grant was made in 1979. Dr. Jack Newton of the USDA in Peoria, Illinois, has done some research on isolation of *Anabaena* from *Azolla*.

Countries that have initiated or plan to initiate azolla research include: India, Nepal, Thailand, Bangladesh, Burma, Indonesia, Malaysia, The Philippines, Sri Lanka, Egypt, Peru, and the West African Rice Development Association, headquartered in Liberia. In addition, several other countries have expressed an interest in the fern and its uses.

What Organizations Are Financing Azolla Research?

Current financial support for azolla research in the U.S. comes from AID (a small 211(d) grant), the National Science Foundation (2 grants), and the USDA (Section 406 and Competitive Grants). The USDA Competitive Grants office has made three grants totaling $278,000 to the University of California at Davis, Ket-

tering Laboratory, and Virginia Commonwealth University. The National Science Foundation has made two grants: one each to University of California at Davis and Kettering Laboratory. In all probability, less than $300,000 per year is now being invested in azolla research in the United States. The work at Hawaii is sponsored by small 211(d) grant for nitrogen fixation from the Agency for International Development and by a research grant from the U.S.D.A. under the Section 406 program of the 1966 Food for Peace Act, and by Hawaii Agricultural Experiment Station funds.

AZOLLA'S EFFECT ON THE NEED FOR AGRICULTURAL INPUTS

Fertilizers

Successful cultivation of azolla requires the application of a certain amount of phosphorus fertilizer (0.5 to 1.0 kg P/ha/week), but this does not necessarily mean an increase in the amount of phosphorus fertilizer required to produce a crop of rice. The application of phosphorus is usually necessary for a good crop of rice, but instead of applying it directly to the rice, the phosphorus can be given to the azolla first in small weekly applications. Once the azolla is incorporated into the soil and begins to decompose, the phosphorus becomes available for the rice crop. Thus phosphorus originally intended for the rice crop is first cycled through the azolla. The phosphorus enables the azolla to grow and fix nitrogen that will be used by the rice. One kilogram of phosphorus applied to azolla results in the fixation of 5 kilograms of nitrogen. North Vietnam is deficient in petroleum products for the production of nitrogen fertilizer, but has sufficient phosphate deposits to fuel its miniature azolla nitrogen factories.

In certain deficient soils, azolla responds to the applications of other nutrients such as potassium, but these usually must also be applied for a high yielding rice crop. In some rare deficient soils, the addition of small amounts of molybdenum and/or iron have proved useful to increase azolla's rate of nitrogen fixation. The Chinese often apply river mud, ash, and animal manure to supplement the phosphorus given to azolla.

Pesticides

Azolla is attacked by larvae of several species of moths and midges and by certain kinds of snails and beetles. These pests are especially destructive during the summer season and must be carefully controlled or the azolla can be devastated. However, azolla is usually not cultivated on a large scale during the seasons when insects are rampant, but is maintained in oversummering nurseries. In addition, even when azolla is cultivated in the field during the summer season, the pesticides normally used on rice crops, such as diptenex, sumithion, malathion, and carbofuran are usually adequate for controlling azolla insects.

Irrigation

Azolla is a delicate, freefloating aquatic plant. Although it can last for months in a refrigerator, it cannot survive for more than a few hours on a dry soil surface under direct summer sunlight. Since technology has not been developed for the use of azolla seeds (spores) in cultivation, a small amount (1 to 10 percent of inoculation requirements) of azolla plants must be maintained through the seasons when azolla is not being cultivated in the fields. This means that in tropical and subtropical areas a certain amount of water must be available throughout the year either to maintain azolla in nurseries or to cultivate it in the fields. The oversummering maintenance of azolla should not be a problem in regions where standing

water is present throughout the year, such as in Bangladesh, or in regions where azolla can be maintained in small nurseries beside mountain springs.

The period when irrigation is most critical is when azolla is to be grown in the fields as a green manure. If azolla is cultivated as a monocrop before the rice, which is the most effective way, water must be available for flooding the fields. If water is not available, azolla cultivation will have to be delayed until it can be grown as an intercrop with the rice. Azolla grows as an intercrop with rice during the first 20 to 30 days after transplanting. In this period, the paddy fields must remain flooded with at least a few centimeters of water. Although some species of azolla can survive on mud, as is commonly seen in Hawaiian taro fields, they need standing water for good growth. Thus rice paddies dependent upon rain water, where short periods of drought often occur during the first month of rice cultivation, will not be suitable for azolla cultivation. Also, if extremely hot periods occur when water temperatures exceed 40° C, cooler water must be available for pumping into the fields to prevent the azolla from dying of heat stress.

Even though azolla cultivation require some extra irrigation water, it must be remembered that in fields where little or no nitrogen fertilizer is used, the cultivation of azolla will significantly increase the efficiency of water use. If azolla increases the yield of rice from 2.5 tons to 5 tons, then the efficiency of water use has nearly doubled.

Machinery

The need for machinery is not a handicap to successful azolla cultivation. Even the most primitive villages can manufacture the basic tools required for the cultivation of azolla. These are made from such locally available raw materials as bamboo and wood. A simple metal/wood tool, costing a few dollars, for incorporating intercropped azolla into the soil can be manufactured in villages by a blacksmith. This tool is not essential, but is more efficient than soil incorporation by hand. An even more efficient multiple row incorporating machine, with a small gas engine, would have to be manufactured commercially.

THE POTENTIAL USE OF AZOLLA

How Does Azolla Affect the Productivity of Tropical Soils?

Azolla affects soils in the same way as any other nitrogen-fixing green manure. It contributes nitrogen, which, after water, is the most common limiting factor to higher crop yields. The application of nitrogen to increase crop yields is the cornerstone of the "green revolution." All new rice varieties are bred for high yielding response to nitrogen fertilizers.

The loss of organic matter is a primary cause of decreasing crop yields in the Tropics. A decrease in soil organic matter results in soil structure deterioration, lower plant nutrient reserves from the organic matter, and a lower cation exchange capacity. Cultivated tropical soil tend to have lower organic matter contents and soil nitrogen than undisturbed tropical soils. This is especially true with Oxisols and Ultisols.

The Potential Use of Azolla

What is the likelihood of Azolla's widespread use? Azolla is cultivated as a green manure on about 2 percent of the harvested rice area of China and about 5 percent of the spring rice crop. In Vietnam, azolla is grown as a winter green manure for 8 to 12 percent of the country's total harvested rice area, and about 40 to 60 percent of the irrigated spring rice in the

Red River delta. Estimates of China's terrestrial green manure crop (mostly legumes) are as high as 7 million hectares, or about five times the total estimated cultivation area of azolla.

As strains or species of azolla are found that are less sensitive to high water temperatures during summer, the areas of azolla in China and Vietnam will probably expand.

The major areas where azolla should prove useful in rice production in the Tropics are those where: 1) rice is transplanted, 2) labor is plentiful, and 3) some control of irrigation water is possible. Also, countries with effective research and extension services may have more success with popularization of azolla.

Azolla technology is not applicable yet for areas where rice is broadcast-sown, except as a monocrop, preplant, basal green manure. An azolla mat can suppress tiny, broadcast-sown rice seedlings; for that reason, intercropped azolla will probably not be successful in broadcast-sown rice unless it is inoculated in the fields after the rice seedlings have become established and are growing well above the water surface.

With the above criteria in mind, the most likely countries to adopt azolla include parts of India, Bangladesh, Thailand, Indonesia, Philippines, Nepal, Peru, and the Dominican Republic.

A RESEARCH, DEVELOPMENT, AND IMPLEMENTATION PROGRAM

The Program Elements

Two basic azolla management systems need research attention; these are: 1) tropical, labor intensive systems; and 2) temperate, capital intensive systems. The tropical systems will be focused mainly on developing countries, and will include these principles:

- labor intensive,
- land intensive,
- small farm based,
- crop intensive,
- maximizing opportunities for year-round production,
- first priority to more intensive use of azolla in transplanted rice systems, and
- second priority to use in broadcast-sown systems.

The tropical program should set the following objectives:

1. To find azolla varieties that are less sensitive to high water temperatures (above 27° C) and pest and disease attack. This would have the effect of expanding azolla use from its present primary role as a spring green manure and its secondary role as a fall green manure to the point where it could be a primary green manure in summer in transplanted rice.
2. To collect and characterize all of the six known azolla species, and to evaluate them for use year-round in tropical transplanted rice production systems. [Note: in 1980 preliminary studies by Lumpkin and his Chinese co-workers in China, *A. microphylla* shows great promise as a summer green manure in south Central China, and a winter green manure in the south. Also, *A. nilotica* shows promise as a fall green manure in China. Neither of these species has ever been tested in rice before. Further mission-oriented research could have high payoff in the near future.]
3. After characterization and early testing, distribute promising strains to national program centers for synthesis, design, and testing of new rice cropping systems based on azolla as a green manure.

Temperate, capital-intensive rice production systems, primarily centered on broadcast-sown or drill-sown rice. This work should focus on developed countries, and on middle-income countries (e.g., Brazil and Colombia, and other countries, primarily in Latin America where similar rice production systems are used).

What Organizations Should Be Involved?

In the United States there are two places where azolla is being studied for use in agriculture. The University of California at Davis is conducting research on azolla for use in temperate zone, broadcast-sown rice, and would be the logical leader for the temperate rice work. The University of Hawaii has a program on evaluation of azolla for use in tropical production systems, and would be the logical leader for the tropical efforts. Kettering Laboratory, Virginia Commonwealth University and USDA have specialized programs that could play supporting basic research roles for the temperate and tropical programs.

Links to developing countries will be necessary. Important programs elsewhere include the Zhejiang Academy of Agricultural Sciences, Hangzhou People's Republic of China, (the University of Hawaii has a cooperative program there already); the Fujian Province, PRC (IRRI has links with this group); IRRI, and national programs in Thailand, India, and Nepal. Several national research programs were initiated after an FAO-sponsored azolla training mission by T. A. Lumpkin in 1977. Also T. A. Lumpkin and J. L. Walker of the University of Hawaii, on behalf of the Inter-American Development Bank, visited Uruguay, Brazil, Peru, and Colombia in 1979 to assess the potential for azolla in those countries.

The West African Rice Research and Development Association (WARDA) is also interested in establishing an azolla research program, and they should be tied into the tropical network.

What Is the Necessary Level of Financial Support?

We will speak first of priority areas of research. There is need to carry out several priority activities soon. These include:

- More extensive and complete collection of azolla species and varieties for evaluation in agriculture. Indeed, *collection should take precedence over efforts to breed azolla* because the array of variability available in nature is clearly great, and this should be collected and characterized before beginning breeding programs.
- Characterization of azolla varieties as to tolerance of high and low temperature, phosphorus levels in water, pH, light, and other growing conditions should be of high priority.
- Testing and fitting existing azolla varieties into rice production systems should receive high priority.

These three priority areas should receive first attention for funding. Related basic research on physiology of the *Azolla/Anabaena* symbiosis, biochemistry of the association, etc., can probably be funded through basic research grants from NSF or USDA.

The applied aspects of collection, characterization for use in agriculture, and fitting into rice production systems could be done for the Tropics for about $400,000 to $600,000 per year. This would allow funds for collaborative collecting trips to assemble a wider germplasm base, to conduct screening trials for tolerance to the physical and growing environment, and to run first assessments of potential usefulness in production systems. Such funding would also allow some limited funds for working with collaborators in a tropical azolla network. It would be desirable to have some funds for assisting, through small subgrants, the conduct of specific desired research programs in cooperating countries.

Training, both nondegree and degree, should receive attention early in the program. The first training should emphasize azolla research techniques (e.g., many programs have failed because researchers did not know how to keep azolla alive during hot or cold weather). Later, training could begin to stress field management. We believe the general principle to follow in funding azolla research is probably that continuity of funding over the first several years will be more effective than heavy funding over a shorter time. Collecting, characterizing, and evaluating production systems needs to be done by a team that will require continuity for effectiveness. Such a team should in-

clude an algologist or cyanobacteria specialist. It should have access to laboratory, greenhouse, and field facilities. The tropical leading institution should be able to grow azolla in the field at any time of the year, and to grow azolla in such a way that all growth stages can be available at any time.

The temperate program will probably require funding in the same order of magnitude as the tropical program. The temperate network may be easier to establish because: 1) the potential countries involved are either in the developed or middle income categories and therefore may have more resources at their disposal, and 2) the countries' institutional research capacity will be much stronger than those of the tropical LDCs.

Some savings may be made and efficiency gained through close cooperation between the temperate and tropical programs. Joint collection trips and close adherence to jointly—determined protocols for testing and evaluation within the networks should save both time and funds.

What Are the Personnel Requirements?

We believe the major research networks should be oriented toward practical adaptation of azolla to agricultural production. Therefore, agronomists with strong physiology and field production backgrounds will be required. As was previously stated, specialists in blue-green alga should be available in the parent institution or nearby.

The program should provide for laboratory and greenhouse assistance, as well as field workers for the field experiments. It is probable that some of this work may be provided by graduate students and student help and by existing institutional farm staff, but some full-time assistance will be needed.

Research assistantships should be provided in the program; this will get the training program going as early as possible.

What Are the Attitudes of Those Who Would Be Affected?

Most research organizations have become aware of azolla and have some idea as to its potential. A few extension specialists (notably in rice) probably also know something about it. Beyond that, except in China and Vietnam and a few individuals in developed countries, the farmers would know nothing of the plant and its potential use in rice. It may be that since azolla is already used successfully in China and Vietnam it may be easier to popularize elsewhere.

What Are Conducive Conditions for Implementation of the Technology?

Conditions conducive to azolla use in the Tropics include:

- transplanted rice;
- rural labor supply;
- assured water supply and some control of water; and
- also, for now, places that grow spring or late summer/fall rice crops because of the high temperature susceptibility of *A. pinnata* in summer.

For rice in temperate zones, the conducive conditions are much less certain because success has not yet been conclusively demonstrated. Factors thought to be important for broadcast-sown rice include:

- growing cold-tolerant azolla (e.g., *A. filiculoides*) as a monocrop green manure to be incorporated into the soil before sowing;
- growing heat-tolerant, shade-sensitive azolla as an intercrop with the broadcast sown rice during the summer; and
- having an assured source of water to grow the monocrop azolla before planting of rice.

Where Do Conducive Conditions Exist and Where Are They Likely to Develop?

Most of the countries of Asia have conducive conditions for use of azolla. Special opportunities for success seem to be present in Thailand, Bangladesh (aus crop), and the Philippines (irrigated dry season crop). In Latin America, Peru and the Dominican Republic appear to have the proper rice production systems to make Azolla use a possibility.

What Is the Sequence of Steps Leading to Successful Implementation?

The first two things a country must learn to do are how: 1) to keep azolla plant materials alive year-round and 2) to multiply azolla stocks in order to have inoculant materials available for use in the rice crop. Principles for such techniques can be learned in training programs at the network headquarters or azolla research centers. Such techniques need to be taught widely to extension workers and to innovative farmers.

In some conditions in Asia, *A. pinnata*, A. *pinnata* var. *imbricata* and perhaps *A. filiculoides* could be used now as a monocrop basal fertilizer before transplanting of rice. This should be easy to popularize for the late winter or early spring rice crops.

Before azolla is used in rice, however, it should be tested under local conditions. As was stated, keeping azolla alive throughout the year and finding ways to multiply it for field use are the most important steps in beginning a program. The next step is testing under local conditions to find ways to fit it into the existing production system. Use as a basal fertilizer before transplanting is probably easiest, but if the crop cycle doesn't allow time to grow an azolla green manure crop between rice crops, then it will be necessary to grow it as an intercrop. In that case the rice must be grown in rows so that incorporation of the azolla can be done. This is just an illustration of some of the considerations to be dealt with in using azolla in agricultural production systems.

CONSTRAINTS TO THE DEVELOPMENT AND IMPLEMENTATION OF AZOLLA TECHNOLOGY

Scientific Constraints

The global azolla research effort is disorganized and much of the work is repetitious and often useless. Certain problem areas, such as those involving agricultural engineering, have been ignored. Much of the support is going to finance esoteric work, while many of the people doing the research have little understanding of the problems that prevent azolla's widespread use by peasant farmers. Much of the work is involved in trying to improve laboratory specimens of azolla, while the vast differences in wild varieties remain unexamined.

Many of the problems preventing the widespread use of azolla require a multidisciplinary research approach, but so far azolla research has been cloistered into individual departments, even in the international institutes.

Funding agencies can assist in ensuring that azolla research will be directed toward real problems and needs by requiring multidisciplinary, linked efforts that focus on use of azolla on farms. This does not mean that basic research will be precluded, but it will ensure that practical, mission-oriented research will not be neglected.

Environmental Constraints

Water is the primary environmental constraint to the cultivation of azolla. Azolla is a freefloating aquatic fern and is therefore limited to locations that have an abundant, stable water supply during field cultivation.

Temperature and humidity: For practical purposes, azolla survives within the water temperature range of 0 to 40 °C; beyond this range,

death will result. For adequate growth during field cultivation, the daytime water temperature should stay within the range of 15° to 35°C. Humidity and temperature interact in their effect on azolla. Very high humidity and high temperature or very low humidity and low temperature are both detrimental to the growth of azolla.

pH: The pH of the paddy water plays an important part in the ability of azolla to survive. Besides directly affecting the growth of azolla, pH also affects the availability of nutrients, especially phosphorus. Low pH and high pH can cause formation of insoluble compounds that tie up available phosphorus; the phosphorus in such insoluble compounds is unavailable to azolla. Azolla grows best within a pH range of 5 to 7 and can survive a range of 3.5 to 10.

Available nutrients: Azolla growth depends on an adequate supply of essential elements in the water or in the surface layer of mud. These elements must also be relatively balanced. Usually the addition of phosphorus and sometimes potassium is all that is necessary to ensure good growth.

Cultural and Economic Constraints

For most farmers, azolla cultivation would be an entirely new way of using green manure. The idea of using an aquatic plant for such purposes is not part of most agricultural heritages. Farmers in tropical Asia traditionally have grown upland legume crops, such as milk vetch or lentils (as a cash crop), after harvesting the monsoon rice crop. Most have never grown an aquatic green manure, and many have rarely grown a legume that is not a food or forage crop. To some, especially the hungry, growing a crop that is to be plowed under as a green manure may seem impractical.

Azolla can be used as a forage for pigs, ducks, and fish. However, the raising of swine, ducks, and fish is uncommon in some places. Also, it is generally believed, although untested, that cattle and water buffalo will not eat azolla.

The year-round cultivation of azolla is more complex than the cultivation of rice. Without support, many poor uneducated rice farmers probably would not or could not grow azolla. Diligent rice farmers, such as those in Nepal or Thailand, probably could master azolla cultivation techniques, just as farmers in China and Vietnam have. As a result of unfavorable land ownership patterns, low grain prices, and other social or economic difficulties, some peasant rice farmers do little more than haphazardly plant their fields and then wait for harvest time. For them, meticulous farming does not yield sufficient benefits to their family. Furthermore, transplanted rice in some parts of Asia is not planted in rows, a necessary measure for azolla to be incorporated as a basal fertilizer.

Also, many farmers who could not be convinced to use nitrogen fertilizer in the 1960s when it was inexpensive, will be unlikely to cultivate azolla. The exceptions might be peasant farmers who want to improve their crop yields but do not have the capital to purchase nitrogen fertilizers. Also, farmers who have given up using nitrogen fertilizer because of the high cost might be convinced to use azolla as long as they can afford the cash outlay for relatively small amounts of phosphorus fertilizer and pesticides. They would have to purchase about 100 kg of single superphosphate to grow one hectare of azolla for 4 to 5 weeks. If properly applied, the phosphorus would result in as much nitrogen as 500 kg of commercial ammonium sulfate fertilizer.

Azolla cultivation could significantly reduce the fertilizer input costs of raising high yielding rice crops, but would still require the purchase of certain inputs, especially phosphorus fertilizer. Farmers unable to obtain these inputs would probably find it difficult or impossible to raise azolla.

Political Constraints

The widespread cultivation of azolla is found only in Communist countries. Azolla was cultivated in both China and Vietnam before

the present governments came to power, but on only a small fraction of the area that azolla covers today. Analyzing the elements of this situation is difficult because the cultivation of azolla in China and Vietnam cannot be compared to its cultivation in countries with different political systems. Because azolla cultivation is just being introduced to farmers elsewhere, there has been insufficient time for other countries to develop successful azolla programs that are in line with their political systems.

Even without an adequate comparison, it is obvious that the successful azolla programs in China and Vietnam owe a considerable amount to the way their farming systems are organized. The commune and cooperative organizations of these countries that use azolla have highly trained azolla teams, whose sole function is to ensure the success of azolla cultivation. Training workshops to learn the newest techniques are held annually from the national level down to the local azolla team level. In addition, every level regularly publishes pamphlets about the practical applications of azolla.

The higher levels of the Chinese and Vietnamese systems can be transferred with minor modifications to other countries, but not the lower local levels. Most governments do not have the power to enforce their will on independent peasant farmers as effectively as China and Vietnam can influence their communes and cooperatives. Nor can a peasant farmer be expected to master all the intricacies of successful azolla cultivation that are known by a highly trained commune azolla team.

THE EFFECT OF THE IMPLEMENTATION OF AZOLLA TECHNOLOGY ON THE NEED FOR INPUTS

Capital

Capital requirements for azolla cultivation are quite small. For most farmers, only a small amount of phosphorus fertilizer, often no more than would be required for the rice crop, and pesticides to protect the azolla from pests and diseases are all that will be required.

Farm Labor

In essence, the cultivation of azolla exchanges labor for nitrogen fertilizer. The present azolla technology is based on the Chinese and Vietnamese models and thus is extremely labor intensive. In fact, the cultivation of azolla cannot be adopted by countries with mechanized rice farming systems until new capital intensive technology is developed.

Adoption of azolla cultivation by a developing country can only increase the demand for farm labor, especially when nursery stocks are being multiplied and during field cultivation. In addition, a few workers will have employment year-round because of the need to maintain azolla nurseries during the off season.

Rice requires about 20 kg of nitrogen per ton of the harvested crop. About half of this is recycled into the soil in the crop residue; therefore about 10 kg of nitrogen is removed per ton of harvested grain. A 6 ton rice harvest removes about 60 kg of nitrogen from the soil, equivalent to 300 kg of ammonium sulfate fertilizer. If azolla was substituted for ammonium sulfate, nearly all of the money required to purchase the 300 kg of ammonium sulfate fertilizer could theoretically be used to pay farm labor to grow azolla, or to gain a greater return on family labor.

Azolla appears to offer special opportunities for small farms, particularly family farms with abundant labor. Conversely, suitable azolla technology for large mechanized farms is not available.

Azolla is used successfully on large communes in China, but the organization of these communes is difficult to relate to family farms.

Land

The land required for azolla cultivation mainly is related to nursery and field multiplication. For overwintering or oversummering, very small protected greenhouse or field areas are required, more in the area of small garden plots than large field areas. However, when azolla multiplication for field inoculation is to be achieved, much more land is required. Perhaps as much as 10 percent of the rice crop area to be inoculated is a good estimate of the land area needed for azolla field multiplication. This land is not tied up permanently, however, but it will be devoted to azolla multiplication for a month or so prior to inoculation.

For farming systems that use azolla as a basal, soil incorporated green manure before the rice crop, all of the land to be planted into rice and fertilized with azolla will need to be devoted to azolla cultivation for about a month prior to transplanting.

In situations where azolla is used as a soil-incorporated, top-dressed green manure or as an unincorporated intercrop with rice, no land will be required to be devoted solely to azolla, except for the inoculation nurseries.

CONCLUSIONS

Azolla is being used as a primary source of nitrogen on an increasing land area in transplanted rice crops in China and Vietnam. The largest use of azolla in these countries is in the spring rice crop, mostly as a monocrop grown before rice as a basal, soil-incorporated green manure. Less is used as an intercropped top-dressing green manure in transplanted rice that is planted in rows.

Use of azolla in the summer rice crop is hampered by high water temperatures and heavy pest attack. A search for suitable temperature-tolerant species or varieties could have high payoff.

Species used in agriculture today are: *A. pinnata, A. pinnata* var. *imbricata* (sometimes referred to as *A. imbricata,* and *A. filiculoides. A. pinnata* and *imbricata* have been used for a long time in China and Vietnam, but their susceptibility to high temperatures and pest attack makes them suitable only for spring and some fall rice crops. *A. filiculoides* has just begun to be used widely in China, especially in areas where—because of its cold tolerance—it can be grown in late winter and early spring as a green manure for early spring rice. Although *A. filiculoides* has proved useful in China because of its cold tolerance, it is even less tolerant of high water temperatures (above 25° to 27° C) than *A. pinnata.* What is needed, then, is an azolla that can tolerate high summer temperatures, up to 40° C or so. *A. microphylla,* collected by T. Lumpkin in the Galapagos Islands, shows promise of becoming a suitable summer green manure for central China and a winter green manure in south China.

There is a great need to collect and characterize species and varieties of azolla extant in nature. This work is of the highest priority. The potential worth of *A. microphylla* in China has already been mentioned. However, it may be useful to point out that *A. nilotica,* collected by T. Lumpkin in the Sudan, has shown the highest nitrogen fixation of any azolla studied. Lumpkin was only able to collect three specimens of *A. nilotica,* yet many more strains and types are available in the Nile Basin and these should be collected and characterized as soon as possible.

All species could prove useful. For example, varieties of *filiculoides* look promising now for use in certain agricultural situations. The same can be said about *microphylla, imbricata, pinnata,* and *caroliniana.*

Research programs should stress multidisciplinary approaches, with close links between

38-846 O - 85 - 5

institutions. Both tropical and temperate farming systems should be emphasized, but these programs should be centered in different places. Both temperate and tropical research programs should be linked, and should cooperate in collection and characterization of species and varieties. The tropical program should focus on using azolla in tropical farming systems, notably small peasant farms, and the temperate program should focus on capital intensive mechanized rice production systems. An international meeting should be held that will have as its major agenda item the setting of international research priorities for azolla. The primary focus of research programs should be to find a useful role for azolla in farming systems. Basic research should not be neglected, but the potential usefulness of azolla is too great to delay its wider use in agriculture through emphasis on more esoteric topics at the expense of applied research.

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Chapter VIII

Using Zeolites in Agriculture

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Contents

	Page
Introduction	127
Natural Zeolites	127
Chemistry and Crystal Structure of Zeolites	128
Properties of Zeolites	129
Applications in Agronomy	133
Fertilizer and Soil Amendments	133
Pesticides, Fungicides, Herbicides	135
Heavy Metal Traps	135
Applications in Animal Husbandry	136
Animal Nutrition	136
Poultry	136
Swine	136
Ruminants	139
Excrement Treatment	141
Malodor and Moisture Control	141
Methane Purification	142
Aquacultural Applications	143
Nitrogen Removal From Closed or Recirculation Systems	143
Aeration Oxygen Production	144
Fish Nutrition	144
Occurrence and Availability of Natural Zeolites	144
Geological Occurrence	144
Geographic Distribution	146
Mining and Milling	149
Discussion	150
Agronomic Applications	150
Animal Nutrition Applications	151
Excrement Treatment Applications	152
Conclusions and Recommendations	152
References	155

Tables

Table No.	Page
1. Representative Formulae and Selected Physical Properties of Important Zeolites	129
2. Growth Response of Radishes to Ammonium-Exchange Clinoptilolite	134
3. Growth Response of Radishes to Natural Clinoptilolite Plus Urea	134
4. Caloric Efficiencies of Zeolite Supplements in Poultry Feeding	136
5. Apparent Caloric Efficiency of Zeolite in Chicken Rations	137
6. Caloric Efficiency of Zeolite Supplements in Swine Feeding	137
7. Effect of Zeolite Diets on Health of Swine	138
8. Effect of Prenatal Zeolite Diet on Newborn Pigs	138
9. Effect of Zeolite Supplement in the Diets of Early Weaned Pigs	139
10. Effect of Zeolite Supplement in Molasses-Based Diets of Young Pigs	139
11. Effect of Clinoptilolite Supplemental in the Diet of Swine	140
12. Occurrence of Diarrhea and Soft-Feces Among Calves on Diets Supplemented With 5% Clinoptilolite	141
13. Effect of Zeolite Additions to Chicken Droppings	142
14. Effect of Clinoptilolite Additions to the Diet of Trout	144
15. Reported Occurrences of Sedimentary Zeolites	148
16. Countries Engaged in Zeolite Mining	150
17. Organizations Engaged in Zeolite/ Agronomic Investigations	151
18. Organizations Engaged in Animal Nutrition Studies Using Zeolites	152
19. Zeolite Property Holders and Zeoagricultural Research Efforts	153

Figures

Figure No.	Page
1. Simple Polyhedron of Silicate and Aluminate Tetrahedra	130
2. Arrangements of Simple Polyhedra to Enclose Large Central Cavities	130
3. Solid Sphere Models of Synthetic Zeolite and Chabazite	131
4. Stylized Illustration of the Entry of Straight-Chain Hydrocarbons and Blockage of Branch-Chain Hydrocarbons at Channel Apertures	131
5. Langmuir-Type Isotherm for Adsorption on Crystalline Zeolites Illustrating Almost Complete Saturation at Low Partial Pressures of the Adsorbate	131
6. Types of Ion-Exchange Isotherms for the Reaction $A_s + B_z = A_z + B_s$	132
7. Change of Soil Nitrogen of Paddy Soil With Time	133
8. Yield of Chrysanthemums as a Function of Potassium Level Supplied by One-Time Additions of Clinoptilolite	134
9. Cumulative Leachate NO_3-N for Banded NH_4-Exchanged Clinoptilolite and Banded Ammonium Sulfate	135
10. Methane-Purification System, Palos Verde Landfill	142
11. Field Exposure of Zeolite Beds	145
12. Scanning Electron Micrograph of Clinoptilolite Laths With Minor Mordenite From a Saline-Lake Deposit Tuff Near Hector, CA	146

Chapter VIII

Using Zeolites in Agriculture

INTRODUCTION

As agriculturalists the world over increase their effort to expand crop and animal production, more and more attention is being paid to various mineral materials as soil amendments and as dietary supplements in animal husbandry. The close relationship between the agricultural and geological sciences is not new—crop production depends on the existence and maintenance of fertile soil and agronomists rely on knowledge of mineralogy and geochemistry of clays and other soil constituents. In the animal sciences, the addition of crushed limestone to chicken feed to strengthen egg shells is well known, as is the use of bentonite as a binding agent in pelletized animal feedstuffs.

Recently, one group of minerals has emerged as having considerable potential in a wide variety of agricultural processes. This group of minerals is the zeolite group. The unique ion-exchange, dehydration-rehydration, and adsorption properties of zeolite materials promise to contribute significantly to many years of agricultural and aquacultural technology (60).

Most of the initial research on the use of zeolites in agriculture took place in the 1960s in Japan. Japanese farmers have used zeolite rock for years to control the moisture content and malodor of animal wastes and to increase the pH of acidic volcanic soils. The addition of small amounts of the zeolites clinoptilolite and mordenite to the normal protein diet of pigs, chickens, and ruminants gave noticeable increases in the body weight and general "health" of the animals (52). The use of zeolites in rations also appeared to reduce odor and associated pollution problems and to provide a means of regulating the viscosity and nitrogen retentivity of animal manure. These same zeolites were also found to increase the ammonium content of rice paddy soils when added with normal fertilizers.

Although most of these were preliminary results and often published in rather obscure journals or reports from local experiment stations, they did suggest that zeolites could act as traps or reservoirs for nitrogen both in the body and in the soil. The growing awareness of such phenomena and of the availability of inexpensive natural zeolites in the Western United States and in geologically similar parts of the world has aroused considerable commercial interest. Zeolites are fast becoming the subject of serious investigation in dozens of agricultural laboratories both here and abroad. Some of the ways in which zeolites can contribute to more efficient crop and livestock production are discussed below, along with their role in the rapidly expanding areas of fish breeding and aquaculture. At this stage, the number of published papers dealing with "zeo-agriculture" is quite small, and hard data are few; however, the potential of these materials in such areas is apparent, and zeolites show promise of contributing directly to increased agricultural productivity in the years to come.

NATURAL ZEOLITES

Zeolites are crystalline, hydrated aluminosilicates of alkali and earth metals that possess infinite, three-dimensional crystal structures. They are further characterized by an ability to lose and gain water reversibly and to exchange some of their constituent elements without major change of structure. Zeolites were discovered in 1756 by Freiherr Axel Fredrick Cronstedt, a Swedish mineralogist, who named them from the Greek words meaning "boiling

stones," in allusion to their peculiar frothing characteristics when heated before the mineralogist's blowpipe. Since that time, nearly 50 natural species of zeolites have been recognized, and more than 100 species having no natural counterparts have been synthesized in the laboratory. Synthetic zeolites are the mainstays of the multimillion-dollar molecular sieve businesses that have been developed by Union Carbide Corp., W. R. Grace & Co., Mobil Corp., Norton Co., Exxon Corp., and several other companies in the last 25 years in the United States and by chemical firms in Germany, France, Great Britain, Belgium, Italy, Japan, and the Soviet Union.

Natural zeolites have long been known to members of the geological community as ubiquitous, but minor constituents in the vugs and cavities of basalt and other traprock formations. It was not until the late 1950s that the world became aware of zeolites as *major* constituents of numerous volcanic tuffs that had been deposited in ancient saline lakes of the Western United States or in thick marine tuff deposits of Italy and Japan. Since that time, more than 2,000 separate occurrences of zeolites have been reported from similar sedimentary rocks of volcanic origin in more than 40 countries. The high purities and near-surface location of the sedimentary deposits has prompted intense commercial interest both here and abroad. Many industrial applications based on the exciting bag of chemical and physical tricks of zeolites have been developed.

The commercial use of natural zeolites is still in its infancy, but more than 300,000 tons of zeolite-rich tuff is mined each year in the United States, Japan, Bulgaria, Hungary, Italy, Yugoslavia, Korea, Mexico, Germany, and the Soviet Union. Natural zeolites have found applications as fillers in the paper industry, as lightweight aggregate in construction, in pozzolanic cements and concrete, as ion-exchangers in the purification of water and municipal sewage effluent, as traps for radioactive species in low-level wastewaters from nuclear facilities, in the production of high purity oxygen from air, as reforming petroleum catalysts, as acid-resistant adsorbents in the drying and purification of natural gas, and in the removal of nitrogen compounds from the blood of kidney patients (58).

The applications and potential applications of both synthetic and natural zeolites depend, of course, on their fundamental physical and chemical properties. These properties are in turn related directly to the chemical composition and crystal structure of individual species.

CHEMISTRY AND CRYSTAL STRUCTURE OF ZEOLITES

Along with quartz and feldspar, zeolites are "tektosilicates," that is, they consist of three-dimensional frameworks of silicon-oxygen $(SiO_4)^{-4}$ tetrahedra, wherein all four corner oxygen atoms of each tetrahedron are shared with adjacent tetrahedra. This arrangement of silicate tetrahedra reduces the overall oxygen: silicon ratio to 2:1, and if each tetrahedron in the framework contains silicon as its central atom, the structures are electrically neutral, as is quartz (SiO_2). In zeolite structures, however, some of the quadrivalent silicon is replaced by trivalent aluminum, giving rise to a deficiency of positive charge. This charge is balanced by the presence of mono- and divalent elements such as sodium (Na^+), calcium (Ca^{2+}), and potassium (K^+) elsewhere in the structure. Thus, the empirical formula of a zeolite is of the type:

$$M_{2/n}O \cdot Al_2O_3 \cdot xSiO_2 \cdot yH_2O$$

where M is any alkali or alkaline earth element, n is the valence charge on that element, x is a number from 2 to 10, and y is a number from 2 to 7. The empirical and unit-cell formulae of clinoptilolite, the most common of the natural zeolites, is:

$$(Na,K)_2O \cdot Al_2O_3 \cdot 10SiO_2 \cdot 6H_2O \text{ or}$$
$$(Na_4K_4)(Al_8Si_{40})O_{96} \cdot 24H_2O.$$

Elements or cations within the first set of parentheses in the formula are known as exchangeable cations; those within the second set

of parentheses are called structural cations, because with oxygen they make up the tetrahedral framework of the structure. Loosely bound molecular water is also present in the structures of all natural zeolites, surrounding the exchangeable cations in large pore spaces.

Whereas the framework structures of quartz and feldspar are dense and tightly packed, those of zeolite minerals are remarkably open and void volumes of dehydrated species as great as 50 percent are known (table 1). Each zeolite species has its own unique crystal structure and, hence, its own set of physical and chemical properties. Most structures, however, can be visualized as SiO_4 and AlO_4 tetrahedra linked together in a simple geometrical form. This particular polyhedron is known as a truncated cubo-octahedron. It is more easily seen by considering only lines joining the midpoints of each tetrahedron, as shown in figure 1.

Individual polyhedra may be connected in several ways; for example, by double four-rings of oxygen atoms (figure 2a), or by double six-rings of oxygen atoms (figure 2b), the framework structures of synthetic zeolite A and the mineral faujasite, respectively. Solid-sphere models of synthetic zeolite A and of the mineral chabazite are illustrated in figures 3a, 3b.

Once the water is removed from a zeolite, considerable void space is available within both the simple polyhedra building blocks and the larger frameworks formed by several polyhedra. Although water and other inorganic and organic molecules would appear to be able to move freely throughout a dehydrated zeolite framework, the passageways leading into the simple polyhedra are too small for all but the smallest molecules to pass; however, ports or channels up to 8 A in diameter lead into the large, three-dimensional cavities (figures 2a, 2b, 3a, 3b).

Properties of Zeolites

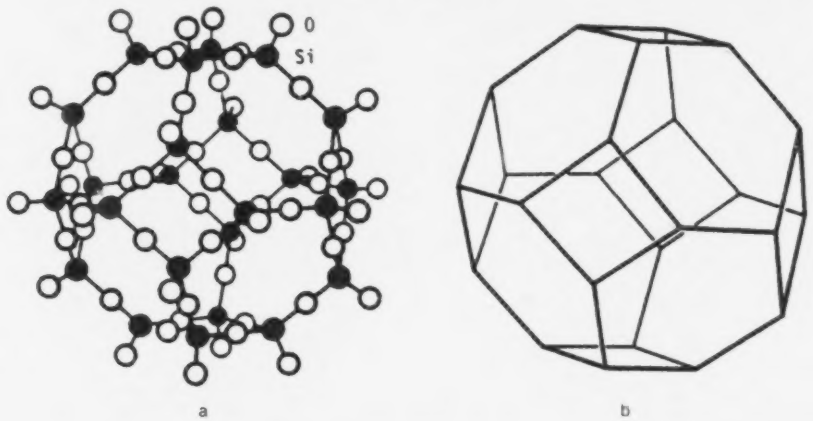
Adsorption properties: Under normal conditions, the large cavities and entry channels of zeolites are filled with water molecules forming hydration spheres around the exchangeable cations. Once the water is removed, usually by heating to 300° to 400° C for a few hours, molecules having diameters small enough to fit through the entry channels are readily adsorbed on the inner surfaces of the vacant central cavities. Molecules too large to pass through the entry channels are excluded, giving rise to the well-known "molecular sieving" property of most crystalline zeolites (figure 4).

Table 1.—Representative Formulae and Selected Physical Properties of Important Zeolites

Zeolite	Representative unit-cell formula[a]	Void volume[a]	Channel dimensions[a]	Thermal stability	Ion-exchange capacity[b]
Analcime	$Na_{16}(Al_{16}Si_{32}O_{96}) \cdot 16H_2O$	18%	2.6 A	High	4.54 meq/g
Chabazite	$(Na_2,Ca)_6(Al_{12}Si_{24}O_{72}) \cdot 40H_2O$	47	3.7 × 4.2	High	3.81
Clinoptilolite	$(Na_4K_4)(Al_8Si_{40}O_{96}) \cdot 24H_2O$	39?	3.9 × 5.4	High	2.54
Erionite	$(Na,Ca_{0.5},K)_9(Al_9Si_{27}O_{72}) \cdot 27H_2O$	35	3.6 × 5.2	High	3.12
Faujasite	$Na_{58}(Al_{58}Si_{134}O_{384}) \cdot 27H_2O$	47	7.4	High	3.39
Ferrierite	$(Na_2Mg_2)(Al_6Si_{30}O_{72}) \cdot 18H_2O$		4.3 × 5.5 3.4 × 4.8	High	2.33
Heulandite	$Ca_3(Al_6Si_{28}O_{72}) \cdot 24H_2O$	39	4.0 × 5.5 4.4 × 7.2 4.1 × 4.7	Low	2.91
Laumontite	$Ca_4(Al_8Si_{16}O_{48}) \cdot 16H_2O$		4.6 × 6.3	Low	4.25
Mordenite	$Na_8(Al_8Si_{40}O_{96}) \cdot 24H_2O$	28	2.9 × 5.7 6.7 × 7.0	High	2.29
Phillipsite	$(Na,K)_{10}(Al_{10}Si_{22}O_{64}) \cdot 20H_2O$	31	4.2 × 4.4 2.8 × 4.8 3.3	Low	3.87
Linde A	$Na_{12}(Al_{12}Si_{12}O_{48}) \cdot 27H_2O$	47	4.2	High	5.48
Linde X	$Na_{86}(Al_{86}Si_{106}O_{384}) \cdot 264H_2O$	50	7.4	High	4.73

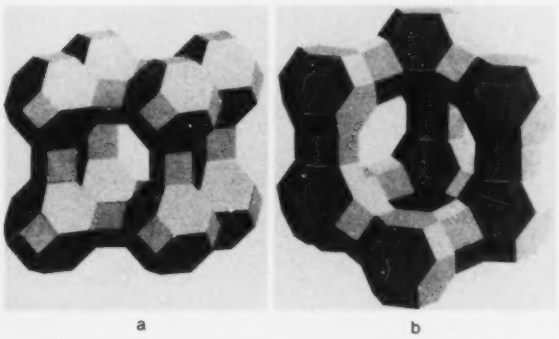
[a]Taken mainly from Breck, 1974; Meier and Olson, 1971. Void volume is determined from water content.
[b]Calculated from unit-cell formula.

Figure 1.—Simple Polyhedron of Silicate and Aluminate Tetrahedra



(a) Ball and peg model of truncated cubo-octahedron. (b) Line drawing of truncated cubo-octahedron; lines connect centers of tetrahedra.

Figure 2.—Arrangements of Simple Polyhedra to Enclose Large Central Cavities



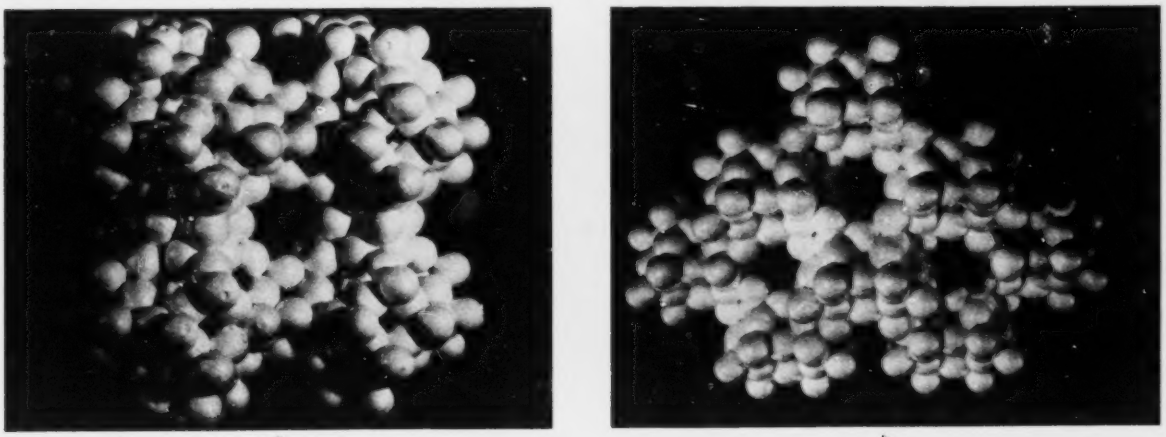
(a) Truncated cubo-octahedra connected by double four-rings of oxygen in structure of synthetic zeolite A. (b) Truncated cubo-octahedra connected by double six-rings of oxygens in structure of faujasite.

The internal surface area available for adsorption ranges up to several hundred square meters per gram, and some zeolites are capable of adsorbing up to about 30 weight percent of a gas, based on the dry weight of the zeolite.

In addition to their ability to separate gas molecules on the basis of size and shape, the unusual charge distribution within a dehydrated void volume allows many species with permanent dipole moments to be adsorbed with a selectivity unlike that of almost all other sorbents. Thus, polar molecules such as water, sulfur dioxide, hydrogen sulfide, and carbon dioxide are preferentially adsorbed by certain zeolites over nonpolar molecules, such as methane, and adsorption processes have been developed using natural zeolites by which carbon dioxide and other contaminants can be removed from impure natural gas or methane streams, allowing the gas to be upgraded to high-Btu products. In addition, the small, but finite, quadripole moment of nitrogen allows it to be adsorbed selectively from air by a dehydrated zeolite, producing oxygen-enriched streams at relatively low cost at room temperature. Both of the above processes may find application in agricultural technology.

Dehydration-rehydration properties: Because of the uniform nature of the pores of structural cages, crystalline zeolites have fairly narrow pore-size distributions, in contrast to other commercial adsorbents, such as activated alumina, carbon, and silica gel. Adsorption on zeolites is therefore characterized by Langmuir-type isotherms, as shown in figure 5. Here, percent of adsorption capacity is plotted against partial pressure of the adsorbate gas. Note that almost all of the zeolite's adsorption capacity for

Figure 3.—Solid Sphere Models of Synthetic Zeolite and Chabazite



a b

(a) Solid-sphere model of the crystal structure of synthetic zeolite A. (b) Solid-sphere model of the crystal structure of chabazite.

Figure 4.—Stylized Illustration of the Entry of Straight-Chain Hydrocarbons and Blockage of Branch-Chain Hydrocarbons at Channel Apertures

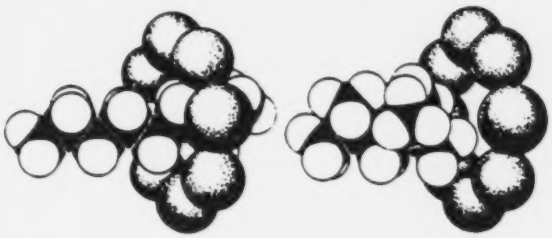
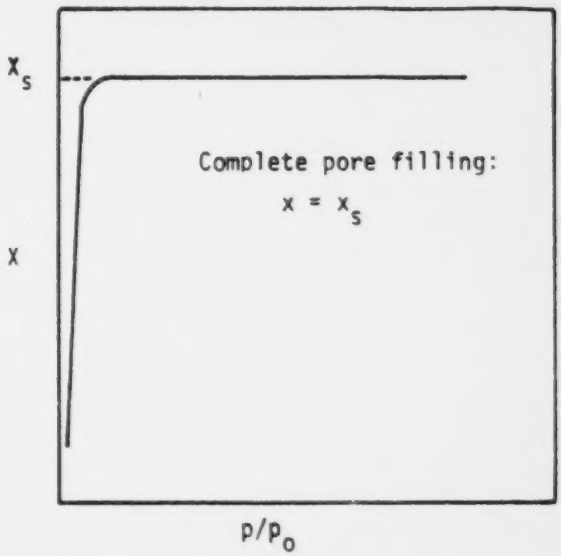


Figure 5.—Langmuir-Type Isotherm for Adsorption on Crystalline Zeolites Illustrating Almost Complete Saturation at Low Partial Pressures of the Adsorbate



x = amount adsorbed; p = pressure.

a particular gas (including water) is obtained at very low partial pressures, meaning that although their total adsorption capacity may be somewhat less than those of other adsorbents, (e.g., silica gel), zeolites are extremely efficient adsorbents even at low partial pressures. This property has been used in the zeolitic adsorption of traces of water from Freon gas lines of ordinary refrigerators that might otherwise freeze and clog pumps and valves. The extreme nonlinearity of the water adsorption isotherms of zeolites has been exploited recently in the development of solar-energy refrigerators (81).

Ion-exchange properties: The exchangeable cations of a zeolite are also only loosely bonded to the tetrahedral framework and can be removed or exchanged from the framework structure easily by washing with a strong solution of another element. As such, crystalline zeolites are some of the most effective ion exchangers known to man, with capacities of 3 to 4 meq per gram being common. This com-

pares with the 0.8 to 1.0 meq per gram cation-exchange capacity of bentonite, the only other significant ion-exchanger found in nature.

Cation-exchange capacity is basically a function of the degree of substitution of aluminum for silicon in the zeolite framework: the greater the substitution, the greater the charge deficiency of the structure, and the greater the number of alkali or alkaline earth atoms required for electrical neutrality. In practice, however, the cation-exchange capacity is dependent on a number of other factors as well. In certain species, cations can be trapped in structural positions that are relatively inaccessible, thereby reducing the effective exchange capacity of that species for that ion. Also, cation sieving may take place if the size of the exchanging cation is too large to pass through the entry channels into the central cavities of the structure.

Unlike most noncrystalline ion exchangers, such as organic resins or inorganic aluminosilicate gels (mislabeled in the trade as "zeolites"), the framework of a *crystalline* zeolite dictates its selectivity toward competing ions. The hydration spheres of high-charge, small-size ions (e.g., sodium, calcium, magnesium) prevent their close approach in the cages to the seat of charge of the framework; therefore ions of low charge and large size (e.g., lead, barium, potassium), that normally do not have hydration spheres are more tightly held and selectively taken up from solution than are other ions. The small amount of aluminum in the composition of clinoptilolite, for example, results in a relatively low cation-exchange capacity (about 2.3 meq/g); however, its cation selectivity is:

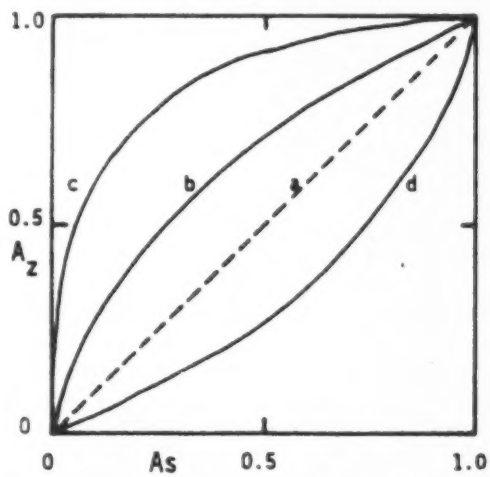
Cesium > Rubidium > Potassium > Ammonium > Barium > Strontium > Sodium

Calcium > Iron > Aluminum > Magnesium > Lithium (3).

Synthetic zeolite A, on the other hand, is more selective for calcium than for sodium, and thus, acts as a water softener in laundry detergents where it picks up calcium from the wash water and releases sodium (75).

Cation exchange between a zeolite (Z) and a solution (S) is usually shown by means of an exchange isotherm that plots the fraction of the exchanging ion (X) in the zeolite phase against that in the solution (figure 6). If a given cation shows no preference of either the solution or the zeolite, the exchange isotherm would be the straight line "a" at 45°. If the zeolite is moderately or very selective for the cation in solution, curve b and c would result, respectively. If the zeolite is rejective of a particular cation, curve d would result. Such is the selectivity of clinoptilolite for cesium or ammonium, for example. Clinoptilolite will take up these ions readily from solutions even in the presence of high concentrations of competing ions, a facility that was exploited by Ames (4) and Mercer, et al. (50), in their development of an ion-exchange process to remove ammoniacal nitrogen from sewage effluent.

Figure 6.—Types of Ion-Exchange Isotherms for the Reaction $A_s + B_z = A_z + B_s$



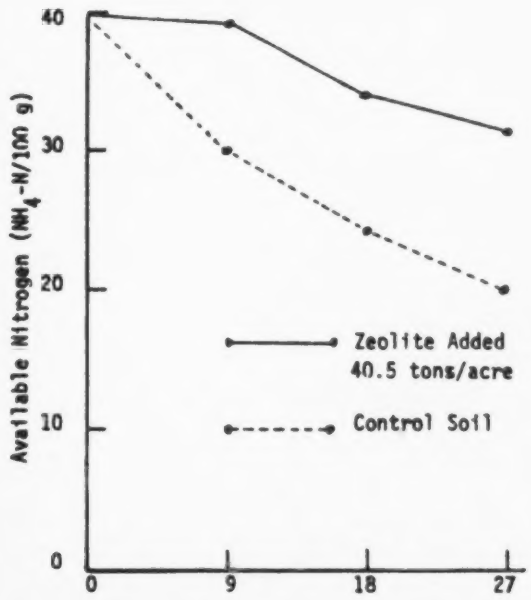
(a) no preference of the ion for either the zeolite or the solution; (b) small preference of the ion for the zeolite phase; (c) large preference of the ion for the zeolite; (d) small preference of the ion for the solution phase. (From Breck, 1974.)

APPLICATIONS IN AGRONOMY

Fertilizer and Soil Amendments

Based on their high ion-exchange capacity and water retentivity, natural zeolites have been used extensively in Japan as amendments for sandy soils, and small tonnages have been exported to Taiwan for this purpose (52,31). The pronounced selectivity of clinoptilolite for large cations, such as ammonium and potassium, has also been exploited in the preparation of chemical fertilizers that improve the nutrient-retention ability of the soils by promoting a slower release of these elements for uptake by plants. In rice fields, where nitrogen efficiencies of less than 50 percent are not uncommon, Minato (52) reported a 63 percent improvement in the amount of available nitrogen in a highly permeable paddy soil 4 weeks after about 40 tons/acre zeolite had been added along with standard fertilizer (figure 7). Turner (84), on the other hand, noted little change in the nitrification of added ammonia when clinoptilolite was mixed with a Texas clay soil, although the overall ion-exchange capacity of the soil was increased. He attributed these conflicting results to the fact that the Japanese soils contained much less clay, thereby accounting for their inherent low ion-exchange capacity and fast-draining properties. The addition of zeolite, therefore, resulted in a marked improvement in the soil's ammonium retentivity. These conclusions support those of Hsu, et al. (31), who found an increase in the effect of zeolite additions to soil when the clay content of the soil decreased. Although additions of both montmorillonite and mordenite increase the cation-exchange capacity of upland soils, the greater stability of the zeolite to weathering allowed this increase to be retained for a much longer period of time than in the clay-enriched soils (22).

Figure 7.—Change of Soil Nitrogen of Paddy Soil With Time

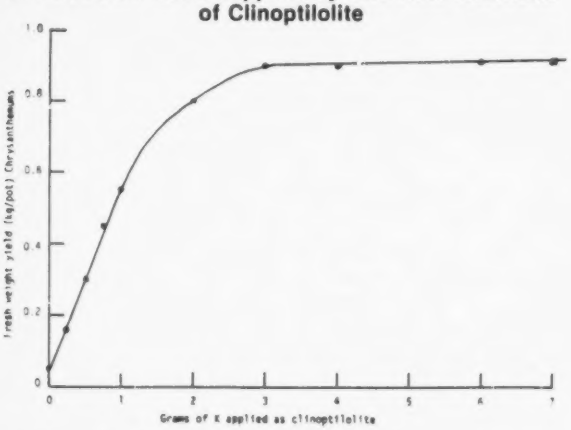


Vertical water seepage in soil = 1.35 cm/day. (Yamagata Prefecture Board of Agriculture and Forestry, 1966; reported in Minato, 1968.)

Using clinoptilolite tuff as a soil conditioner, the Agricultural Improvement Section of the Yamagata Prefectural Government, Japan, reported significant increases in the yields of wheat (13 to 15 percent), eggplant (19 to 55 percent), apples (13 to 38 percent), and carrots (63 percent) when from 4 to 8 tons of zeolite was added per acre (83). Small, but significant improvements in the dry-weight yields of sorghum in greenhouse experiments using a sandy loam were noted when 0.5 to 3.0 tons of clinoptilolite per acre was added along with normal fertilizer (47). However, little improvement was found when raising corn under similar conditions. Hershey, et al. (29), showed that clinoptilolite added to a potting medium for chrysanthemums did not behave like a soluble K source, but was very similar to a slow-release fertilizer. The same fresh-weight yield was achieved with a one-time addition of clinoptilolite as with a daily irrigation of Hoagland's solution, containing 238 ppm K, for three months (total of 7 g potassium added), with no apparent detrimental effect on the plants (figure 8).

Experiments by Great Western Sugar Co. in Longmont, CO, using clinoptilolite as a soil amendment, resulted in a significant increase

Figure 8.—Yield of Chrysanthemums as a Function of Potassium Level Supplied by One-Time Additions of Clinoptilolite



Solid square represents total of 7 g of potassium supplied by daily irrigation with Hoaglan's solution containing 234 ppm K. Total time of experiment was 3 months. (From Hershey, et al., 1980.)

in total-matter production of sugar beets, although "high" levels of zeolite were required (1). The details of these experiments are considered proprietary and have not been released. The addition of ammonium-exchanged clinoptilolite in greenhouse experiments with radishes resulted in a 59- and 53-percent increase in root weight in medium and light clay soils, respectively (45). The nitrogen uptake by plant tops also increased with the zeolite treatment compared with an ammonium sulfate control (table 2). These authors also found that natural clinoptilolite added to soil in conjunction with urea reduced the growth suppression that normally occurs when urea is added alone (table 3). The presence of zeolites also resulted in less NO_3-N being leached from the soil (figure 9).

Both zeolite treatments apparently made considerably more ammonium available to the plants, especially when clay-poor soils were employed. The authors suggested that ammonium-exchanged clinoptilolite acted as a slow-release fertilizer, whereas, natural clinoptilolite acted as a trap for ammonium that was produced by the decomposing urea, and thereby prevented both ammonium and nitrate toxicity by disrupting the bacterial nitrification process. The ammonium selectivity of zeolites was exploited by Varro (85) in the formulation of a fertilizer consisting of a 1:1 mixture of sewage sludge and zeolite, wherein the zeolite apparently controls the release of nitrogen from the organic components of the sludge.

Coupled with its valuable ion-exchange properties which allow a controlled release of micronutrients, such as iron, zinc, copper, man-

Table 2.—Growth Response of Radishes to Ammonium-Exchange Clinoptilolite[a]

Parameter	13% clay soil[b]		6% clay soil[c]	
	NH_4-Clinoptilolite	$(NH_4)_2SO_4$	NH_4-Clinoptilolite	$(NH_4)_2SO_4$
Leaf area (cm^2/plant)	243	187	187	150
Plant weight (dry weight) (g)	1.84	1.12	1.40	1.1
Root weight (g)	13.5	8.5	11.6	7.6
N uptake (mg N/plant top)	57.2	35.9	42.6	38.9

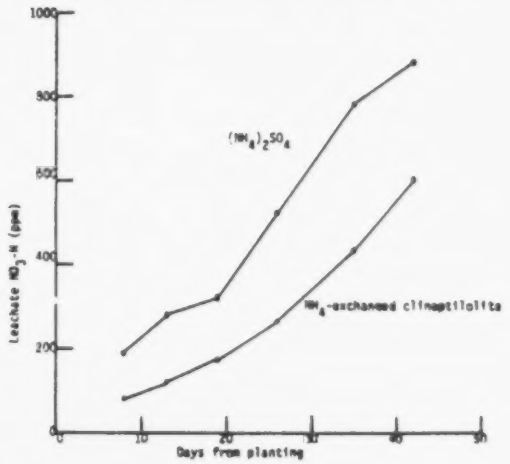
[a]Lewis, *et al.*, 1980.
[b]Plants sampled 36 days after planting.
[c]Leached five times; plants sampled 34 days after planting.

Table 3.—Growth Response of Radishes to Natural Clinoptilolite Plus Urea[a]

Parameter	13% clay soil[b]		6% clay soil[c]	
	Zeolite + Urea	Urea	Zeolite + Urea	Urea
Leaf area (cm^2/plant)	210	187	208	116
Plant weight (dry weight) (g)	1.59	1.23	1.38	0.71
Root weight (g)	13.8	9.2	12.4	6.3
N uptake (mg N/plant top)	45.5	38.6	44.4	18.9

[a]Lewis, *et al.*, 1980.
[b]Plants sampled 36 days after planting.
[c]Leached five times; plants sampled 34 days after planting.

Figure 9.—Cumulative Leachate NO_3-N for Banded NH_4-Exchanged Clinoptilolite and Banded Ammonium Sulfate (Lewis, et al., 1980)



ganese, and cobalt, the ability of clinoptilolite to absorb excess moisture makes it an attractive addition to chemical fertilizers to prevent caking and hardening during storage and to animal feedstuffs to inhibit the development of mold (82). Spiridonova, et al. (78), found that 0.5 percent clinoptilolite added to ammonium nitrate fertilizer decreased caking by 68 percent.

Pesticides, Fungicides, Herbicides

Similar to their synthetic counterparts, the high adsorption capacities in the dehydrated state and the high ion-exchange capacities of many natural zeolites make them effective carriers of herbicides, fungicides, and pesticides. Clinoptilolite can be an excellent substrate for benzyl phosphorothioate to control stem blasting in rice (88). Using natural zeolites as a base, Hayashizaki and Tsuneji (26) found that clinoptilolite is more than twice as effective as a carrier of the herbicide benthiocarb in eliminating weeds in paddy fields as other commercial products. Torii (82) reported that more than 100 tons of zeolite were used in Japan in 1973 as carriers in agriculture. A Russian patent was issued to Aleshin, et al. (2), for grouting compound containing 3 to 5 percent clinoptilolite to control herbicide percolation from irrigation canals to ground waters.

Heavy Metal Traps

Not only do the ion-exchange properties of certain zeolites allow them to be used as carriers of nutrient elements in fertilizers, they can be exploited to trap undesirable metals and prevent their uptake into the food chain. Pulverized zeolites effectively reduced the transfer of fertilizer-added heavy metals, such as copper, cadmium, lead, and zinc, from soils to plants (18). The selectivity of clinoptilolite for such heavy metals has been noted by several workers (e.g., 74,19,11,76).

In view of the attempts being made by sanitary and agricultural engineers to add municipal and industrial sewage sludge to farm and forest soils, natural zeolites may play a major role in this area also. The nutrient content of such sludges is desirable, but the heavy metals present may accumulate to the point where they become toxic to plant life or to the animals or human beings that may eventually eat these plants. Cohen (12) reported median values of 31 ppm cadmium, 1,230 ppm copper, 830 ppm lead, and 2,780 ppm zinc for sludges produced in typical U.S. treatment plants. Zeolite additives to extract heavy metals may be a key to the safe use of sludge as fertilizer and help extend the life of sludge-disposal sites or of land subjected to the spray-irrigation processes now being developed for the disposal of chlorinated sewage. Similarly, Nishita and Haug (64) showed that the addition of clinoptilolite to soils contaminated with radioactive strontium (Sr^{90}) resulted in a marked decrease in the uptake of strontium by plants, an observation having enormous import in potential treatment of radioactive fallout that contaminates soils in several Pacific atolls where nuclear testing has been carried out.

APPLICATIONS IN ANIMAL HUSBANDRY

Animal Nutrition

Based on the successful use of montmorillonite clay in slowing down the passage of nutrients in the digestive system of chickens and the resultant improvement in caloric efficiency (73), experiments have been carried out in Japan since 1965 on the application of natural zeolites as dietary supplements for several types of domestic animals. Because much of this work was superficial or not statistically significant, it has been repeated and enlarged upon in recent years by researchers in the United States and several other countries seeking agricultural applications for zeolites.

Poultry

Using clinoptilolite from the Itaya mine, Yamagata Prefecture, and mondenite from Karawago, Miyagi Prefecture, Onagi (67) found that Leghorn chickens required less food and water and still gained as much weight in a 2-week trial as birds receiving a control diet. Feed efficiency values (FEV)[1] were markedly higher at all levels of zeolite substitution; feedstuffs containing 10 percent zeolite gave rise to efficiencies more than 20 percent greater than those of normal rations (table 4). Adverse effects on the health or vitality of the birds were not noted, and the droppings of groups receiving zeolite diets contained up to 25 percent less moisture than those of control groups, after a 12-day drying period, making them considerably easier to handle.

Broiler chickens fed a diet of 5 percent clinoptilolite from the Hector, CA, deposit gained slightly less weight over a 2-month period than birds receiving a normal diet, but average FEVs were noticeably higher (table 5) (6). Perhaps of greater significance is the fact that none of the 48 test birds on the zeolite diet died during the experiment, while 3 on the control diet and 2 on the control diet supplemented with antibiotics succumbed. In addition to an apparent feed-efficiency increase of 4 to 5 percent, the presence of zeolite in the diet appears to have had a favorable effect on the mortality of the birds.

Hayhurst and Willard (27) confirmed many of Onagi's observations and reported small increases in FEV for Leghorn roosters over a 40-day period, especially during the first 10 days. The birds were fed a diet containing 7.5 percent clinoptilolite crushed and mixed directly with the normal rations. Feces were noticeably dryer and less odoriferous. Unfortunately, only 17 birds were used in the study and extensive statistical evaluation of the results could not be made.

Swine

Kondo and Wagai (39) evaluated the use of zeolites in the diets of young and mature Yorkshire pigs in 60- and 79-day experiments, re-

[1]Weight gain/feed intake, excluding zeolite.

Table 4.—Caloric Efficiencies of Zeolite Supplements in poultry Feeding[a]

Group no.	Zeolite content of rations	Average starting wt. (g)	Average final wt. (g)	Average weight gain (g)	Average feed intake[b] (g)	Feed efficiency ratio[c]
1	10 percent Cp[d]	553.7	795.6	241.9	668	0.362
2	5 percent Cp	540.7	778	237.3	697	0.340
3	3 percent Cp	556.7	796	239.3	748	0.320
4	10 percent Mo	532.3	757.3	225.0	634	0.355
5	5 percent Mo	552.3	814.6	262.3	775	0.338
6	3 percent Mo	534.5	791.3	256.8	769	0.334
7	Control	556.5	789.3	232.8	782	0.298

[a]Onagi (1965). Tests carried out on 48-day-old Leghorns over a 14-day period, 30 birds/group. Normal rations consisted of 16.5 percent crude protein and 66 percent digestible nutrients.
[b]Excluding zeolite.
[c]Feed efficiency = weight gain/feed intake (excluding zeolite).
[d]Cp = clinoptilolite; Mo = mordenite.

Table 5.—Apparent Caloric Efficiency of Zeolite in Chicken Rations[a]

Treatment of	Average weight (g)	Average consumption[b] (g)	Average F.E.V.[c]	Survivors of 48 birds
		4-week data[d]		
Control diet	730	1175	0.622	46
Control diet + antibiotics[e]	708	1116	0.634	47
Control diet with 5 percent clinoptilolite	703	1070	0.657	48
		8-week data[f]		
Control diet	1869	3978	0.470	45
Control diet + antibiotics	1882	3869	0.486	46
Control diet with 6 percent clinoptilolite	1783	3647	0.489	48

[a]Adapted from data of Arscott (1975).
[b]Feed consumed, excluding zeolite.
[c]Feed efficiency value = weight/feed consumed (excluding zeolite).
[d]Starter rations (0 to 4 weeks).
[e]55 ppm zinc bacitracin.
[f]Finisher rations (4 to 9 weeks).

spectively, and found that the weight gain of animals of both ages receiving diets containing 5 percent clinoptilolite was from 25 to 29 percent greater than that of animals receiving normal diets (table 6). Feed supplemented with zeolites gave rise to feed efficiencies about 35 percent greater than those of normal rations when fed to young pigs, but only about 6 percent greater when given to older animals. In addition, the particle size of the feces of the control group was noticeably coarser than that of the experiment group, suggesting that the digestive process was more thorough when zeolites were added to the diet. The feces of animals in the control group were also richer in all forms of nitrogen than zeolite-fed animals, indicating that the zeolites contributed toward a more efficient conversion of feedstuff nitrogen to animal protein.

The digestibility of crude protein and nitrogen-free extracts tended to be improved as zeolite was substituted for wheat bran in swine diets at levels from 1 to 6 percent over a 12-week period (24,26). Anai, et al. (5), reported similar results using 5 percent zeolite for 8 pigs over a 12-week period and realized a 4-percent decrease in the cost of producing body weight. They also noted a decrease in malodor and moisture content of the excrement. Toxic or other adverse effects were not noted for any of the test animals described. On the contrary, the presence of zeolites in swine rations appears to contribute measurably to the well-being of the animals. Tests carried out on 4,000 head of swine in Japan showed that the death rate and incidence of disease among animals fed a diet containing 6 percent clinoptilolite was markedly lower than for control animals over a 12-month period (83). As shown in table 7, the decrease in the number of cases of gastric ulcers, pneumonia, heart dilation, and in the overall mortality is remarkable. The savings in medicine alone amounted to about 75 cents per animal, to say nothing of the increased value of a larger number of healthy pigs.

In one test, the addition of zeolite to the diet of piglets severely afflicted with scours markedly reversed the progress of this disease within a few days (53). Four underdeveloped Laundry

Table 6.—Caloric Efficiency of Zeolite Supplements in Swine Feeding[a]

	Age of pigs		Average weight					
	Start	Finish	Start	Finish	Average	Average[b]	Average[c]	Zeolite
	(days)		(kg)	(kg)	wt. gain (kg)	feed intake (kg)	F.E.V.	improvement
Experimental[d]	60	120	15.43	44.43	29.00	85.0	0.341	
Control[d]	60	120	14.85	35.78	22.93	90.6	0.253	35 percent
Experimental[e]	99	178	30.73	85.30	54.57	167.6	0.326	
Control[e]	99	178	31.20	73.50	42.30	136.2	0.308	6 percent

[a]Kondo and Wagai (1968). Tests carried out using 5 percent clinoptilolite in rations of experimental groups.
[b]Excluded zeolite.
[c]Feed efficiency value = weight gain/feed intake.
[d]Eight Yorkshire pigs.
[e]Twenty Yorkshire pigs.

Table 7.—Effect of Zeolite Diets on Health of Swine[a]

Period	Zeolite content of rations	Sickness causes		Heart dilatation	Mortality rate (percent)	Medicine cost/head
		Gastric ulcer	Pneumonia			
2/72 to 1/73	0	77	128	6	4.0	$2.50
2/73 to 1/74	6 percent clinoptilolite	22	51	4	2.6	$1.75

[a]Test carried out on 4,000 swine at Kesi Farm, Morioka, Iwate Perfecture, Japan (Torii, 1974)

pigs were fed a diet containing 30 percent zeolite for the first 15 days and 10 percent zeolite for the remaining part of a month-long experiment. The severity of the disease decreased almost at once, and feces of all pigs were hard and normal after only 7 days. Although the pigs consumed an average of 1.75 kg of zeolite per head per day, no ill effects were noted, and once they had recovered from diarrhetic ailments, the pigs regained healthy appetites and became vital. A recent Japanese patent disclosure claimed a method of preventing and treating gastric ulcer in swine by the addition of zeolite to their diets (49); supportive data, however, were not reported.

Apparently the vitalizing effect of a zeolite diet can be transferred from mother to offspring. Experiments at the Ichikawa Livestock Experiment Station, where 400 g of clinoptilolite was fed each day to pregnant sows and continued through the 35-day weaning period of their offspring, showed substantial increase in the growth rate of the young pigs. As shown in table 8, test animals weighed from 65 to 85 percent more than control-group animals at the end of the weaning period (9). Young pigs whose dams received the zeolite diet also suffered almost no attacks of diarrhea, while those in control groups were severely afflicted with scours, greatly inhibiting their normal growth. The addition of 5 percent zeolite to the rations of pregnant sows 20 to 90 days after mating gave rise to improved FEVs and increased litter weight at parturition (46). The earlier the zeolite was added, the greater was the apparent effect.

Similar studies were conducted at Oregon State University with young swine using rations containing 5 percent clinoptilolite (16). Although lesser increases in growth rates were found than in the Japanese studies, the incidence of scours was significantly reduced for animals receiving the zeolite diet. Currently, heavy doses of prophylactic antibiotics are used to control such intestinal diseases, which, left unchecked, result in high mortality among young swine after they are weaned. Federal regulations are becoming increasingly stringent in this area, and if antibiotics are prohibited, other means must be found to control such diseases. Natural zeolites may be the answer.

In a preliminary study involving 16 early weaned pigs over a 19-day period, animals on an antibiotic-free diet containing 10 percent clinoptilolite gained about 5 percent more weight per pound of feed than those on a control diet without antibiotics and about 4 percent more than those on an antibiotic-enriched diet (table 9) (70). The small number of pigs used, however, limits the significance of these findings. In another study, a 30 percent improvement in FEVs occurred for 35 young pigs on a molasses-based diet when 7.5 percent

Table 8.—Effect of Prenatal Zeolite Diet on Newborn Pigs[a]

Species	No. of pigs	Group	Average weight (kg)			Weight gain improvement[b]
			Newborn	21-days	35-days	
Yorkshire	6	Experimental	1.25	4.3	7.83	
Yorkshire	10	Control	1.10	4.2	4.81	63 percent
Laundry	6	Experimental	1.20	4.7	8.68	
Laundry	10	Control	1.10	4.0	4.67	96 percent

[a]Test carried out at Ichikawa Livestock Experiment Station, Japan. Four hundred grams of clinoptilolite given to sows in experimental group per day and continued to end of weaning period (Buto and Takenashi, 1967).
[b]Weight-gain of experimental animals ÷ weight-gain of control animals × 100.

Table 9.—Effect of Zeolite Supplement in the Diets of Early Weaned Pigs[a]

	Basal diet[b]	Zeolite diet[c]	Antibiotic diet[d]
Number of pigs	4	4	4
Average daily weight gain (g)	245	245	304
Feed efficiency value (FEV)[e] (weight gain/feed intake)	0.432	0.455	0.437

[a]Pond and Mumpton (1978).
[b]62% ground yellow corn, 10% cerelose, 23% soybean meal, 0.5% salt, 0.5% Hopro R vitamin supplement, 1.5% ground limestone, 2.5% dicalcium phosphate.
[c]Basal diet less 10% cerelose plus 10% clinoptilolite, -200 mesh, Castle Creek, Idaho.
[d]Basal diet plus 0.3% Aurofac 10 antibiotic.
[e]Excluding zeolite.

clinoptilolite was substituted in the diet during the 35 to 65 kg growth period (table 10) (10). Feces of the zeolite-fed animals were also less liquid than those on a control diet.

The addition of zeolites had little effect on the FEVs in the 65 to 100 kg growth range. Heeney (28) supplemented normal corn-soy rations of 36 pigs with 2.5 and 5 percent clinoptilolite in a 120-day experiment (table 11). He found little overall difference in the FEVs; however, for the first 30 days after weaning, FEVs of 0.455 and 0.424 were obtained for 2.5 and 5.0 percent zeolite, respectively, compared with a value of 0.382 for the control animals, an increase of about 15 percent due to the presence of zeolites in the diet. Little improvement was noted between 30 and 120 days of the treatment.

Ruminants

In an attempt to reduce the toxic effects of high NH_4+ content of ruminal fluids when nonprotein nitrogen (NPN) compounds, such as urea and diuret, are added to the diets of cattle, sheep, and goats, researchers introduced both natural and synthetic zeolites into the rumen of test animals (87). Ammonium ions formed by the enzyme decomposition of NPN were immediately ion exchanged into the zeolite structure and held there for several hours until released by the regenerative action of Na+ entering the rumen in saliva during the after-feeding fermentation period. Both *in vivo* and *in vitro* data showed that up to 15 percent of the NH_4+ in the rumen could be taken up by the zeolite. Thus, the gradual release of NH_4+ allowed rumen micro-organisms to synthesize cellular protein continuously for easy assimilation into the animals' digestive systems. The zeolite's ability to act as a reservoir for NH_4+ "... permits the addition of supplemental nitrogen to the animal feed while protecting the animal against the production of toxic levels of ammonia" in the rumen (87).

Clinoptilolite added to the feed of young calves improved their growth rate by stimulating appetite and decreased the incidence of di-

Table 10.—Effect of Zeolite Supplement in Molasses-Based Diets of Young Pigs[a]

	Zeolite level (%)				
	0	2.5	5	7.5	10
	35-65 kg growth stage				
Daily gain (g)	621	694	700	704	659
Daily intake[b] (g)	2900	3110	3090	2970	3040
Daily feed intake[c] (g)	2900	3030	2940	2750	2740
Feed efficiency value (FEV)[d] (weight gain/feed intake)	0.214	0.229	0.238	0.256	0.241
	65-100 kg growth stages				
Daily gain (g)	541	582	526	562	535
Daily intake[b] (g)	3550	3900	4260	4430	4140
Daily feed intake[c] (g)	3550	3800	4050	4100	3730
Feed efficiency value (FEV)[d] (weight gain/feed intake)	0.152	0.153	0.130	0.137	0.143

[a]Castro and Elias (1978).
[b]Including zeolite.
[c]Intake less zeolite.
[d]Excluding zeolite.

Table 11.—Effect of Clinoptilolite Supplemental in the Diet of Swine[a]

	Control	2.5% Clinoptilolite	5% Clinoptilolite
Average initial weight (lb)	31.6	31.7	31.7
30-days:			
Average weight (lb)	61.0	62.2	62.5
Average daily weight gain (lb)	1.09	1.12	1.17
Feed/pound of gain (lb)[b]	2.62	2.20	2.36
Feed efficiency value[c]	0.382	0.455	0.424
60-days:			
Average weight (lb)	105.7	107.3	106.2
Average daily weight gain (lb)	1.59	1.61	1.52
Feed/pound of gain (lb)[b]	2.80	3.05	3.09
Feed efficiency value[c]	0.357	0.328	0.324
90-days:			
Average weight (lb)	153.7	149.6	150.0
Average daily weight gain (lb)	1.72	1.51	1.57
Feed/pound of gain (lb)[b]	3.33	3.43	3.67
Feed efficiency value[c]	0.300	0.292	0.272
120-days:			
Average weight (lb)	188.2	177.8	176.4
Average daily weight gain (lb)	1.56	1.28	1.27
Feed/pound of gain (lb)[b]	3.94	5.63	4.30
Feed efficiency value[c]	0.254	0.178	0.233
Overall:			
Average daily weight gain (lb)	1.49	1.40	1.37
Feed/pound of gain (lb)[b]	3.42	3.45	3.34
Feed efficiency value[c]	0.292	0.290	0.299

[a]From Heeney (1977); 6 pigs in each treatment. Control diet = 76.9% ground corn, 20% soybean oil meal, 1.5% dicalcium phosphate, 0.5% $CaCO_3$, 0.5% salt, 0.1% trace mineral, 0.25% vitamin pre-mix, 0.25% ASP250 antibiotic. Zeolite diets contained 2.5 and 5% replacement of corn.
[b]Excluding zeolite.
[c]Weight gain/feed intake, excluding zeolite.

arrhea and soft feces (38). Five percent zeolite was added to the normal grass and hay diets of 10- and 184-day-old heifer calves over a 180-day period. The animals on the zeolite-supplemented diets gained approximately 20 percent more weight than those in control groups, and although the test calves consumed more feed, the feeding costs per kilogram of weight gained were significantly less than for control animals. No deleterious effects were noted, and the feces of the test animals contained slightly less water and fewer particles of undigested solids. The incidence of diarrhea and soft-feces was markedly less in zeolite-fed calves than in control animals (table 12).

Watanabe, et al. (86), raised six young bullocks for 329 days on a diet containing 2 percent clinoptilolite, along with 72 percent digestible nutrients and 11 percent crude protein. Although little difference in the final weights of test and control animals was noted, test steers showed slightly larger body dimensions and reportedly dressed out to give slightly higher quality meat. These differences were reflected in the overall higher prices obtained for the test animals and a 20 percent greater profit. In addition, diarrhea and other intestinal ailments were noticeably less prevalent in the animals on the zeolite diet, and the excrement from these animals was significantly less odoriferous, again testifying to the retentivity of clinoptilolite for ammonia. It is unfortunate that a higher level of zeolite was not used in these experiments; earlier studies in the United States showed that as much as 40 percent clay could be added to animal rations without adverse effects (68).

One study found increased protein digestion when 5 percent powdered clinoptilolite was added to a high-solubility protein diet of 18 Holstein steers and cows over a 118-day period; however, statistically significant weight increases were not noted. The addition of 2 percent zeolite to the rations of cows was effective in preventing diarrhea and in increasing milk production (20). These effects were appar-

Table 12.—Occurrence of Diarrhea and Soft-Feces Among Calves on Diets Supplemented With 5% Clinoptilolite[a]

Time (days)	Incidence of diarrhea			Incidence of soft-feces		
	Grass-fed + zeolite (2 calves)	Hay-fed + zeolite (2 calves	Control group (6 calves)	Grass-fed + zeolite (2 calves)	Hay-fed + zeolite (2 calves)	Control group (6 calves)
30	0	0	4	0	0	4
36-60	0	1	2	9	4	13
61-90	0	0	2	1	1	13
91-120	1	0	1	2	0	13
121-150	0	0	4	4	0	8
151-184	0	0	0	0	0	0
Total	1	1	13	16	5	51

[a]Data summarized from Kondo, et al. (1969).

ently related to an increase in the albumin and a decrease in the urea-N content of the blood.

Excrement Treatment

In the United States, livestock production creates more than 1 billion metric tons of solid waste and nearly 400 million tons of liquid waste each year (43). Accumulations of such magnitude pose serious problems to the health of man and beast alike and can pollute nearby streams and rivers. In addition, the large amount of undigested protein remaining in the excrement represents a valuable resource that for the most part is being wasted because of our growing dependence on chemical fertilizers. The physical and chemical properties of many natural zeolites lend themselves to a wide variety of applications in the treatment of animal wastes, including the:

- reduction of malodor and associated pollution,
- creation of healthier environments for confined livestock,
- control of the viscosity and nutrient retentivity of the manure, and
- purification of methane gas produced by anaerobic digestion of the excrement.

Malodor and Moisture Control

The semifluid droppings in large poultry houses commonly emit a stench that is discomforting to farm workers and to the chickens themselves. The noxious fumes of ammonia and hydrogen sulfide contribute to decreased resistance to respiratory diseases and result in smaller and less healthy birds (15,35). In many areas of Japan clinoptilolite is now mixed with the droppings directly or packed in boxes suspended from ceilings to remove ammonia and thereby improve the general atmosphere in chicken houses (82). The net result is reported to be an overall increase in egg production and healthier birds.

One study used a zeolite-packed air scrubber to improve poultry-house environments (36). By passing ammonia-laden air over a series of trays containing crushed clinoptilolite, 15 to 45 percent of the NH_3-N was removed even though the contact time was less than one second. There was an associated reduction in odor intensity. The use of such a scrubber could improve the quality of the air in poultry houses without the loss of heat that accompanies normal ventilation. The ammonium-loaded zeolite could then be used as a valuable soil amendment on disposal.

Water content, maggot population, and ammonia production can be all minimized when chicken droppings are mixed with one-third zeolite (table 13). Similar results can be obtained if powdered zeolite is added directly to the rations of the birds, all without affecting the vitality or growth rate of the chickens (67). Apparently, gaseous ammonia reacts with the hydrous zeolite to form ammonium ions that are selectively ion-exchanged and held in the zeolite structure. These experiments suggest that the addition of zeolites to poultry wastes could reduce labor costs associated with air-drying or the high energy costs of thermal treat-

Table 13.—Effect of Zeolite Additions to Chicken Droppings[a]

Property	2:1	3:1	5:1	10:1	Control
Moisture content (%)	12.3	13.1	13.4	15.7	18.5
Maggot content (counts per unit area)	38	101	172	387	573
Ammonia generation (relative quantities)	315	370	245	500	450

[a]Onagi (1965). Clinoptilolite was spread on droppings of Leghorn chickens every third day for a 15-day period. The total amount of droppings is the same in all tests, including the control.

ment, while at the same time retain the valuable fertilizer components and meet ecological standards.

In swine raising, pigs fed a diet containing 10 percent clinoptilolite had feces richer in all forms of nitrogen after drying than those from control groups (*vide supra*) (39). As a result of this study and of other investigations, about 25 tons of clinoptilolite per month is spread on the floors of a Sapporo swine-raising facility to adsorb urine and other liquid wastes (82). The buildings were said to be dry, clean, and considerably less odoriferous. In Akita Prefecture, Japan, a zeolitic mudstone is used to treat offensive odors and to reduce moisture content of swine excrement (30). The dried manure is then sold as an inexpensive rice fertilizer.

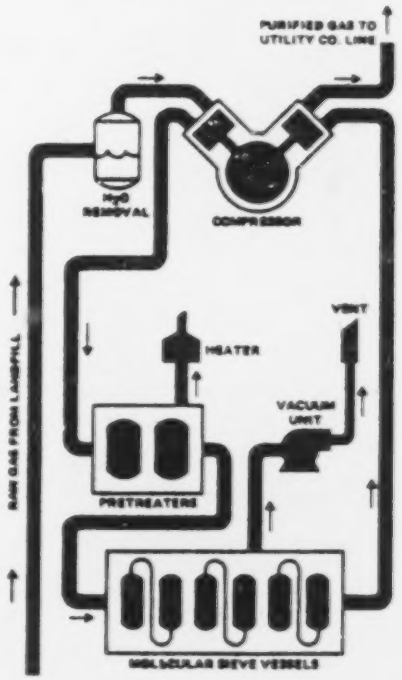
An innovative application of zeolites in excrement treatment was patented and involves the addition of a natural zeolite and ferrous sulfate to chicken droppings (37). The ferrous sulfate inhibits zymosis and decomposition of the droppings, and the zeolite stabilizes the hygroscopic nature of this compound and captures NH_4+ produced in the manure. The mixture is dried at 120° to 150° C and used as an odorless, organic fertilizer. It is also used as a protein-rich feedstuff for fish, fowl, and domestic animals.

Methane Purification

Although it is well known that anaerobic digestion of animal excrement and other organic wastes produces an impure methane-gas product, this source of energy has generally been ignored for anything except local or in-house use (32). One major drawback is the fact that in addition to methane, copious quantities of carbon dioxide and sulfur compounds are also produced during the digestion process, giving rise to low-Btu products that are extremely corrosive. Nevertheless, the process is still an attractive one, and Goeppner and Hasselmann (21) estimated that a billion cubic feet of 700 Btu/ft³ methane gas could be produced by treating the 250,000 tons of manure produced each day in the United States. The methane produced by the anaerobic digestion of the organic wastes of a typical New York State dairy farm of 60 head may be equivalent to the farm's entire fossil-fuel requirements (32).

A recent development of Reserve Synthetic Fuels, Inc., using the adsorption properties of natural zeolites, suggests that this methane can be economically upgraded to high-Btu products. In 1975, this company opened a methane-recovery and purification plant to treat methane gas produced by decaying organic matter in the Palos Verde landfill near Los Angeles. As shown schematically in figure 10, raw gas containing about 50 percent methane and 40

Figure 10.—Methane-Purification System, Palos Verde Landfill



percent carbon dioxide is fed to two pretreatment vessels to remove moisture, hydrogen sulfide, and mercaptans. The dry gas is then routed through three parallel columns packed with pellets of dehydrated chabazite/erionite and carbon dioxide is removed by adsorption on the zeolite. Approximately 1 million cubic feet of methane meeting pipeline specifications is produced each day and delivered to local utility companies (65). Such a zeolite-adsorption process to upgrade impure methane produced by the digestion of animal manure appears to be technically feasible and awaits detailed economic and engineering evaluation.

AQUACULTURAL APPLICATIONS

In recent years, more and more fish products have found their way to the dinner tables and feeding troughs of every country, and the commercial breeding and raising of fish as a source of protein is becoming a major business in the United States and other countries. Many varieties of fish, however, are extremely sensitive to minor fluctuations in such factors as water temperature, pH, O_2, H_2S, and NH_4+. The chemical and biological environment of aquacultural systems must be maintained within close limits at all times. Processes based on the selective adsorption and ion-exchange properties of several natural zeolites for oxygen aeration of hatchery and transport water and for the removal of toxic nitrogen from tanks and breeding ponds may contribute significantly to increased production for human and animal consumption.

Nitrogen Removal From Closed or Recirculation Systems

In closed or recirculating aquacultural systems, NH_4+ produced by the decomposition of excrement and unused food is one of the leading causes of disease and mortality in fish. In oxygen-poor environments, even a few parts-per-million NH_4+ can lead to gill damage, hyperplasia, and substantial reduction in growth rates (42). Biological nitrification is a common means of removing NH_4+ from culture waters; however, processes similar to those used in municipal sewage-treatment plants based on zeolite ion exchange have been found to be effective in controlling the nitrogen content of hatchery waters (40). Zeolite ion exchange might be a useful alternative to biofiltration for NH_4+-removal and have the advantages of low cost and high tolerance to changing temperatures and chemical conditions (33).

Unpublished tests conducted in 1973 at a working hatchery near Newport, OR, indicated that 97 to 99 percent of the NH_4+ produced in a recirculating system was removed by clinoptilolite ion-exchange columns (34). Trout also remained healthy during a 4-week trial when zeolite ion exchange was used to regulate the nitrogen content of tank waters (69). Becker Industries of Newport, OR, in conjunction with the U.S. Army Corps of Engineers, has developed a single-unit purification facility for hatchery-water reuse. The system incorporates a zeolite ion-exchange circuit for nitrogen removal and is designed to handle typical concentrations and conditions encountered at most of the 200 fish hatcheries operating in the Pacific Northwest (34).

A similar ammonium-ion removal system using zeolite ion exchange for fish haulage applications, where brain damage due to excess NH_4+ commonly results in sterility, stunted growth, and high mortality has also been developed (63). Three-way cartridges and filters containing granular clinoptilolite will also be available for home aquaria. The U.S. Fish and Wildlife Service investigated zeolite ion-exchange processes for the treatment of recirculating waters in tank trucks used to transport channel catfish from Texas hatcheries to the Colorado River in Arizona (48). If NH_4+ can be removed, the number of fish hauled in such trucks can be nearly tripled.

Aeration Oxygen Production

Oxygen-enriched air can be produced by the selective adsorption of nitrogen by activated zeolites. A pressure-swing adsorption process capable of producing up to 500 m^3 of 90 percent oxygen per hour was developed in Japan for secondary steel smelting (80). Smaller generators with outputs of as little as 15 liters of 50 percent O_2 per hour are also manufactured and used to aerate fish breeding tanks and in the transportation of live fish. Carp and goldfish raised in such environments are said to be livelier and to have greater appetites (41). In closed tanks and stagnant ponds, oxygen aeration could markedly increase the number of fish that could be raised per unit volume.

Oxygen produced by small, portable units containing natural zeolite adsorbents could be used to replenish free oxygen in small lakes where eutrophication endangers fish life. Fast, et al. (17), showed that the oxygen of hypolimnion zones could be increased markedly by aeration using liquid O_2 as a source. Haines (23) demonstrated side-stream pumping could improve the dissolved oxygen in the hypolimnion of a small lake in New York State.

Fish Nutrition

The high-protein rations used in commercial fish raising are quite expensive and their cost has been a limiting factor in the development of large-scale aquacultural operations. The physiology of fish and poultry is remarkably similar, and if the results achieved with chickens can be duplicated with fish, the substitution of small amounts of inexpensive zeolites in normal fish food, with no adverse change in growth and perhaps a small increase in feed efficiency, could result in considerable savings. The quality of the water in recirculating systems should also be improved by the use of zeolite-supplemented food, as should that of the effluents. Leonard (44) reported preliminary results of experiments where 2 percent clinoptilolite was added to the normal 48 percent protein food of 100 rainbow trout: after 64 days, a 10 percent improvement in the biomass increase was noted, with no apparent ill effects on the fish (table 14).

Table 14.—Effect of Clinoptilolite Additions to the Diet of Trout[a]

	Control 100% normal feed[b]	Test 98% normal feed 2% clinoptilolite
Average starting weight (g)	10.2	10.1
Average 64-day weight	48.6	52.3
Average weight gain	38.4	42.2
Mortality	4	3

[a]100 rainbow trout.
[b]Standard 48% protein fish food.

OCCURRENCE AND AVAILABILITY OF NATURAL ZEOLITES

Geological Occurrence

Since their discovery more than 200 years ago, natural zeolite minerals have been widely recognized by geologists as cavity and fracture fillings in almost every basaltic igneous rock. Attractive crystals up to several centimeters in size adorn the mineral museums of every country; however, such traprock occurrences are generally too low-grade and heterogeneous for commercial extraction. The flat-lying and nearly monomineralic sedimentary deposits, on the other hand, are ideally suited for simple, inexpensive, open-pit mining.

Most sedimentary zeolite deposits of economic significance were formed from fine-grained volcanic ash or other pyroclastic material that was carried by the wind from an erupting volcano and deposited onto the land surface, into shallow freshwater or saline lakes, or into the sea fairly close to the volcanic source. Much of the land-deposited material was quickly washed into lakes where it formed

beds of nearly pure ash. Successive eruptions resulted in sequences of ash layers interstratified with normal lake or marine sediments, such as mudstones, siltstone, sandstones, and limestones, as well as beds of diatomite, bentonite, and chert (figure 11).

The layers of volcanic ash (called volcanic tuff) vary in thickness from less than a centimeter to several hundred meters and may stretch for 10 kilometers. Many of these bedded tuffs have been transformed almost completely into well-formed, micrometer-size zeolite minerals. Zeolitically altered tuffs occur in relatively young sedimentary rocks in diverse geological environments. Sedimentary zeolite deposits of this kind have been classified into the following types, with many gradations between the types, Sheppard (77), Mumpton (54), and Munson and Sheppard (62):

1. deposits formed from volcanic materials in hydrologically "closed" saline-alkaline lake systems;
2. deposits formed in hydrologically "open" fresh-water lake or ground water systems;
3. deposits formed in marine environments;
4. deposits formed by low-grade, burial metamorphism;
5. deposits formed by hydrothermal or hot-spring activity in bedded sediments;
6. deposits formed from volcanic materials in alkaline soils;
7. deposits formed without direct evidence of volcanic precursors.

The most common zeolites in sedimentary deposits are analcime, chabazite, clinoptilolite, erionite, heulandite, laumontite, mordenite, phillipsite, and wairakite, with clinoptilolite ranking first in abundance. Except for heulan-

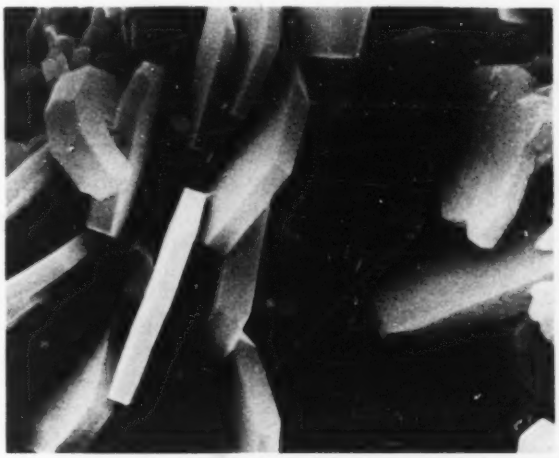
Figure 11.—Field Exposure of Zeolite Beds

dite, laumontite, and wairakite, "sedimentary" zeolites are alkalic and are commonly more silicic than their igneous counterparts. Commercial interest is mainly in deposits of the first four types. Zeolite tuffs in saline-lake deposits are generally a few centimeters to a few meters thick and commonly contain nearly monomineralic zones of the larger pore zeolites, erionite and chabazite that are relatively uncommon in other types of deposits. "Open-system" deposits and marine tuffs deposited close to their source are generally characterized by clinoptilolite and/or mordenite and may be several hundred meters thick. Zeolitic tuffs are commonly soft and lightweight, although some hard, siliceous deposits of clinoptilolite and mordenite are known. Many sedimentary zeolite beds contain as much as 95 percent of a single zeolite species, while others consist of two or more zeolites with minor amounts of calcite, quartz, feldspar, montmorillonite clay, and unreacted volcanic glass.

Most zeolites in sedimentary rocks crystallized from volcanic ash by reaction of the amorphous, aluminosilicate glass with pervading pore waters derived either from saline lakes or descending ground waters. Others originated by the alteration of preexisting feldspars, feldspathoids, biogenic silica, or poorly crystalline clay minerals. Although the exact mechanism of formation is still under investigation, zeolites in sedimentary rocks probably crystallized as well-formed, micrometer-size crystals by means of a dissolution-reprecipitation mechanism, with or without an intermediate gel stage (55) (figure 12).

The factors controlling whether a zeolite or a clay mineral formed or which of several zeolites formed from a given starting material are also only poorly understood, although temperature, pressure, reaction time, and the concentrations of the dissolved species, such as H+, silica, alumina, and alkali and alkaline earth elements, seem to be paramount in importance. Early formed species also tend to react further with pore fluids of different composition, thereby yielding even more complex assemblages.

Figure 12.—Scanning Electron Micrograph of Clinoptilolite Laths With Minor Mordenite From a Saline-Lake Deposit Tuff Near Hector, CA (from Mumpton and Ormsby, 1976)



Geographic Distribution

The distribution of zeolite deposits in various geographic regions of the world is governed solely by the geology of those regions. Regions that have undergone past volcanic activity are likely to contain significant deposits of zeolite minerals. Although the zeolite phillipsite is known to have formed within the last 10,000 years in a small saline-lake deposit at Teels Marsh, NV (79) by the alteration of volcanic ash from the explosion of Mt. Mazuma (Crater Lake), and chabazite has been identified in deposits on the walls of ancient Roman baths in France, most potentially commercial deposits of zeolites are of Tertiary or lower Pleistocene age (70,000 to 3 million years ago). Thus, any part of the Earth that was subjected to volcanic activity during this period undoubtedly contains extensive deposits of volcanic ash, and if these ash deposits had an opportunity to react with percolating ground waters or alkaline pore waters from former saline lakes, beds of high-grade zeolites are apt to exist.

Although zeolites are now considered to be some of the most abundant and widespread au-

thigenic silicate minerals in sedimentary rocks, their existence as major constituents of altered volcanic tuffs is still not common knowledge among the geologists of many countries. Because of their inherently fine crystal size, zeolites are not easily identified by ordinary microscopic techniques and have often been missed by geologists and mineralogists studying these formations. In general, zeolite identification requires sophisticated X-ray diffraction and electron microscopic equipment not available in many geological laboratories; however, once a particular soft, lightweight, clay-like rock from a particular area is identified in the laboratory as a zeolite rock, similar materials are easy to locate in the field.

Table 15 lists the countries where zeolites have been reported from sedimentary rocks of volcanic origin and estimates the chances of discovering additional deposits in these countries. Sedimentary zeolites have been found on every continent, although few have been reported from the Middle East, Latin America, or the East Indies, mainly because geologists in these regions generally have been unaware of the widespread occurrence of zeolites in altered volcanic tuffs. Wherever zeolites have been found, however, man has used the soft, lightweight tuffs for hundreds of years as easily carved stone in a variety of structures ranging from walls and foundations of buildings to barns and corrals to house livestock. Zeolitic blocks have been found in buildings associated with the Mayan pyramids at Monte Alban and Mitla in southern Mexico (56) and are used today in the construction of modern dwellings in the Tokaj region of eastern Hungary. Zeolites are mined in only a dozen countries (table 16), but the potential is much greater.

The high probability of finding minable deposits of zeolites in countries where they have not yet been reported, but where there has been considerable volcanic activity in the past, is illustrated by the discovery of major bodies of sedimentary zeolites in Mexico and in central Turkey in the early and late 1970s, respectively. Both countries show promise of becoming major suppliers of mineral raw materials in the years to come, but, as with most developing nations, they have only limited in-house geological expertise to service their blossoming mineral industry.

During the late 1950s and 1960s the geological similarity of the Western United States and northern Mexico led geologists to speculate about the existence of zeolite deposits south of the border. It was not until 1972, however, that this author (56) discovered the first such deposit in southern Oaxaca after visiting a large stone quarry during an unrelated project. The rock was being used as a local dimension stone and closely resembled zeolitic tuffs that were being quarried in Japan. Subsequently, the Oaxacan rock was shown to consist of about 90 percent clinoptilolite and mordenite. Shortly thereafter, several similar deposits were discovered in this part of Mexico and Mexican scientists quickly learned to recognize zeolitic tuffs in the field. One deposit was spotted in a road cut while driving past it at 50 miles per hour, suggesting that many more await discovery with only minimal exploration efforts. As a result of these discoveries, at least three other deposits of sedimentary zeolites have been found in the northern part of the country by Mexican geologists who are now atune to the existence of zeolites in volcanogenic environments and to their potential applications in industrial and agricultural technology.

Similar to Mexico, major parts of the central Anatolian region of Turkey are covered by thick sequences of Tertiary volcanic rocks, but, with the exception of a few minor occurrences of analcime in saline-lake environments, reports of zeolites in the volcanogenic sedimentary rocks of this country have been rare. The principal reason for this is simply lack of exploration combined with a lack of knowledge about the potential applications of such materials in industry. Turkey's few geologists have been more occupied with their chrome and borate resources, which are exported in large quantities to acquire badly needed currency. In 1977, however, several low-grade occurrences of erionite and chabazite were uncovered in Turkey's Cappadocia region, along with a major deposit of clinoptilolite (7). In 1979, a second major deposit was discovered by the au-

Table 15.—Reported Occurrences of Sedimentary Zeolites

Country	Zeolite species	Minable deposit	Minor occurrence	Chances for finding deposit
Europe:				
Belgium	Laumontite		X	Poor
Bulgaria	Clinoptilolite	XXX		Excellent
	Mordenite	X		Excellent
	Analcime		X	Poor
Czechoslovakia	Clinoptilolite	X		Good
Denmark	Clinoptilolite		X	Poor
Finland	Laumontite		X	Poor
France	Clinoptilolite		XXX	Good
Germany	Chabazite	XX		Good
	Phillipsite	XX		Good
	Analcime		XX	Poor
Great Britain	Analcime		X	Poor
	Clinoptilolite		X	Poor
	Laumontite		X	Poor
Hungary	Clinoptilolite	XX		Excellent
	Mordenite	X		Excellent
Italy	Chabazite	XXX		Excellent
	Phillipsite	XXX		Excellent
	Analcime		X	Good
Poland	Clinoptilolite	XX		Excellent
Romania	Clinoptilolite	XX		Excellent
Soviet Union	Clinoptilolite	XXX		Excellent
	Mordenite	XX		Excellent
	Chabazite		X	Good
	Analcime		X	Good
	Laumontite		X	Good
Spain	Clinoptilolite		X	Good
	Mordenite		X	Good
Switzerland	Clinoptilolite		X	Poor
	Laumontite		XX	Poor
Turkey	Clinoptilolite	XX		Excellent
	Erionite		XX	Excellent
	Chabazite		XX	Excellent
	Analcime	X		Excellent
Yugoslavia	Clinoptilolite	XXX		Excellent
	Analcime	X		Good
	Mordenite	X		Excellent
	Erionite		X	Good
North America.				
Canada	Laumontite		X	Poor
	Clinoptilolite		X	Good
Cuba	Clinoptilolite	XX		Excellent
	Mordenite	X		Excellent
Guatemala	Clinoptilolite	X		Excellent
Mexico	Clinoptilolite	XX		Excellent
	Mordenite	XX		Excellent
	Analcime		X	Good
	Erionite	X		Excellent
	Phillipsite		X	Excellent
Panama	Clinoptilolite	X		Excellent
West Indies	Wairakite		X	Poor
	Clinoptilolite		X	Excellent
Africa:				
Angola	Clinoptilolite		X	Good
Botswana	Clinoptilolite		X	Good
Congo	Analcime	X		Good
Egypt	Heulandite		X	Good
Kenya	Phillipsite	X		Excellent
	Erionite	X		Excellent

Table 15.—Reported Occurrences of Sedimentary Zeolites—Continued

Country	Zeolite species	Minable deposit	Minor occurrence	Chances for finding deposit
Northwest Africa	Analcime	X		Good
	Mordenite		X	Good
	Clinoptilolite	X		Excellent
Republic of South Africa	Analcime		X	Poor
	Clinoptilolite	XX		Excellent
Tanzania	Erionite	X		Excellent
	Chabazite	X		Excellent
	Phillipsite	X		Excellent
	Analcime	X		Excellent
	Clinoptilolite	X		Excellent
Asia:				
Iran	Clinoptilolite	X		Excellent
Israel	Clinoptilolite		XX	Excellent
Pakistan	Analcime		X	Good
Australia	Clinoptilolite	X		Good
	Analcime		X	Good
China	Clinoptilolite	XX		Excellent
Formosa	Laumontite		X	Poor
	Analcime		X	Good
Japan	Clinoptilolite	XXX		Excellent
	Mordenite	XX		Excellent
	Analcime		X	Poor
	Laumontite		X	Poor
	Wairakite		X	Poor
Korea	Clinoptilolite	XX		Excellent
New Zealand	Analcime		X	Good
	Clinoptilolite	XX		Good
	Mordenite	X		Excellent
	Laumontite	X		Good
	Erionite	X		Good
Oceania	Laumontite		X	Poor
South Africa:				
Argentina	Clinoptilolite	XX	Excellent	
	Analcime	X		Excellent
	Laumontite		X	Poor
Chile	Clinoptilolite		X	Excellent
Antarctica:				
Antarctica	Laumontite		X	Poor
	Phillipsite		X	Poor

thor (59) and R. A. Sheppard of the U.S. Geological Survey, accompanied by a Turkish geologist, with a minimum of field effort. This indicates a widespread distribution of such materials in volcanogenic sedimentary rocks in this country.

Mining and Milling

The mining of zeolites in bedded sedimentary deposits is a relatively straightforward process requiring only a minimum of equipment and trained personnel. Almost all of the known zeolite deposits being mined are surface deposits overlain by a few to no more than 25 meters of overburden. The zeolite beds are usually flat-lying and vary only slightly in thickness along the length of the deposit. Shallow drilling is usually required to outline the areas of highest grade, but many deposits are mined by simple projection of the bed behind the outcrop. Commonly, the exposed bed can be broken in the mine by bulldozers or rippers; in places small amounts of blasting are required. In thinner deposits, care must be taken to eliminate overlying and underlying clays and volcanic ash from the ore to preserve purity, but in some of the thicker deposits this poses no problem.

Table 16.—Countries Engaged in Zeolite Mining[a]

Country	Mineral	Mines	Remarks
United States	Clinoptilolite	12	Many more available.
	Chabazite	4	Single deposit, four companies.
	Erionite	2	
	Mordenite	1	
Mexico	Mordenite/Clinoptilolite	1	
Cuba	Clinoptilolite	1	
Japan	Clinoptilolite	8	Estimated.
	Mordenite	5	Estimated.
Korea	Clinoptilolite	2	
Bulgaria	Clinoptilolite	1	
Hungary	Clinoptilolite	1	
	Mordenite	1	Estimated.
Soviet Union	Clinoptilolite	3	Estimated.
	Mordenite	1	Estimated.
Yugoslavia	Clinoptilolite	2	Several more available.
South Africa	Clinoptilolite	1	
Italy	Chabazite/Phillipsite		Numerous, used for construction.
Germany	Chabazite/Phillipsite		Several, used for construction.

[a]As of 1980.

Processing the raw ore is dependent on the envisioned end use. Water-purification applications require a fine-sand fraction that must be prepared from the ore by crushing and screening whereas fertilizer and animal nutrition uses will likely make use of finely powdered material. In general, preparation involves only crushing, screening, and bagging. Where particle size is critical, the screened product must be washed to remove undersize material and then dried. More sophisticated applications may require that the zeolite be ion-exchanged to an ammonium or potassium form before being shipped to the consumer. In such cases, the pulverized and screened product must be subjected to a series of washes with chloride or sulfate salts of these elements, washed with water to eliminate excess salts, filtered, dried, and bagged. In 1980, crushed ore could be produced in the United States for about $30 to $40/ton.

DISCUSSION

Agronomic Applications

Although zeolites have been used for many years in Japan as soil amendments, they are only now becoming the subject of serious investigation in the United States as slow-release fertilizers, moisture-control additives to low-clay soils, traps for heavy metals, carriers of pesticides, fungicides, and herbicides, and de-caking agents in fertilizer storage. As soil amendments they appear to retain moisture and improve the overall ion-exchange capacity of sandy and volcanic soils. Studies are being carried out on both pure zeolite and on zeolite that has been pretreated with nutritive elements, such as potassium or ammonium. In either case, the zeolite appears to act as a slow-release fertilizer, selectively holding such elements in its structure for long periods of time, thereby increasing the efficiency of such additives and reducing the total cost of fertilization. Although the data available are not unequivocal, the greatest success appears to have been with root crops such as sugar beets, carrots, and radishes, where nitrogen is a vital nutrient. The optimum level of application, however, must still be determined for various types of soils and for the particular crop in question, as must the frequency and exact mode of application, the optimum particle size of the zeolite, and the nature of chemical pretreatment of the zeolite.

The ion-exchange specificity of certain zeolites for copper, lead, cadmium, and zinc suggests that the "life" of farm and forest soils amended with municipal and industrial sewage sludge can be extended by inhibiting the plant uptake of these deleterious metals. Radioactive cesium and strontium from nuclear fallout or spills may also be controlled by selective ion exchange into zeolites added to soils. Zeolites apparently are useful carriers of herbicides, pesticides, and fungicides and can prevent caking in stored fertilizers by absorbing excess moisture.

Table 17 lists organizations that have or are conducting experiments on the use of natural zeolites in agronomic applications.

Animal Nutrition Applications

Despite the lack of statistical significance, numerous studies strongly suggest that the addition of certain zeolite minerals to the diets of swine, poultry, and ruminants results in decided improvement in growth and in feed efficiency (weight gain/pounds of nutritional feed consumed). In addition, the incidence of intestinal disease among young animals appears to be less when zeolites are part of the daily diet. The most dramatic results have been reported by overseas workers where experiments may have been conducted under conditions that were somewhat less sanitary than those generally employed in the United States. Zeolite-supplemented diets appear to be most beneficial in swine during the first 30 to 60 days after weaning, although there is some evidence to suggest that zeolites in the rations of pregnant sows contribute to increased litter weights and healthier offspring. In Japan, 2 to 5 percent clinoptilolite in the diets of cattle appeared to result in larger animals and fewer incidences of diarrhea. One study in the United States found a 12-percent increase in feed efficiency for cattle during the first 37 days using only 1.25 percent zeolite.

The exact function of the zeolites in both dietary and antibiotic phenomena are not well understood and await serious physiological and biochemical investigation. The ammonium selectivity of clinoptilolite suggests that in ruminants it acts as a reservoir for ammonium ions produced by the breakdown of vegetable protein and nonprotein nitrogen in rations, releasing it for a more efficient synthesis into amino acids, proteins, and other nitrogenous compounds by micro-organisms in the gastrointestinal (GI) lumen. From the concentration of ammonia in the portal blood of weanling rats fed a 5 percent clinoptilolite diet or dosed orally with this zeolite, Pond, et al. (71), postulated that the zeolite bound free ammonia in the GI tract, thereby preventing its buildup to toxic levels in the system. Such an antibiotic effect could indeed be responsible for the larger growths recorded for zeolite-fed animals.

Table 18 lists organizations that have or are conducting experiments on the use of natural zeolites in animal nutrition applications.

Table 17.—Organizations Engaged in Zeolite/Agronomic Investigations[a]

Organizations	Crop	Organization	Crop
Department of Horticulture Colorado State University Fort Collins, Colorado	Radishes	Agricultural Experiment Station New Mexico State University Las Crucas, New Mexico	Corn Sorghum
Department of Agronomy Colorado State University Fort Collins, Colorado	Sorghum Corn Wheat	Department of Plant Science University of New Hampshire Durham, New Hampshire	Radishes Corn
Department of Environmental Horticulture University of California Davis, California	Chrysanthemums	Texas Agricultural Experiment Station Texas A&M University Beaumont, Texas	Rice
U.S. Sugarcane Field Laboratory U.S. Department of Agriculture Houma, Louisiana	Sugarcane	Department of Soils, Water and Engineering Tucson, Arizona	Nitrogen retention in soils

[a]As of 1980.

Table 18.—Organizations Engaged in Animal Nutrition Studies Using Zeolites[a]

Organization	Animal	Organization	Animal
Department of Poultry Science Colorado State University Fort Collins, Colorado	Chickens	Department of Animal Science Cornell University Ithaca, New York	Swine
Department of Animal Science Colorado State University Fort Collins, Colorado	Swine	Department of Animal Science Oregon State University Corvallis, Oregon	Swine Rabbits
Clayton Livestock Research Center New Mexico State University Clayton, New Mexico	Beef Cattle	Western Washington Research and Extension Center Washington State University Puyallup, Washington	Dairy Cattle
Department of Poultry Science Oregon State University Corvallis, Oregon	Chickens	Department of Animal Science University of Kentucky Lexington, Kentucky	Calves
Livestock Nutrition Service Westminster, California	Cattle	Food and Animal Research, Inc. Juneau, Wisconsin	Calves
Department of Animal Science University of Vermont Burlington, Vermont	Ruminants	Department of Biology Cleveland State University Cleveland, Ohio	Chickens Swine
U.S. Meat Animal Research Center U.S. Department of Agriculture Clay Center, Nebraska	Rats (swine)	Department of Agricultural Engineering Oregon State University Corvallis, Oregon	Odor control
Department of Animal Science Pennsylvania State University University Park, Pennsylvania	Cattle		

[a]As of 1980.

Excrement Treatment Applications

Although the results are difficult to quantify, almost all studies of the use of zeolites as dietary supplements in animal rations have reported a noticeable decrease in excrement malodor and have attributed this observation to the high selectivity of the zeolite in the feces for the ammonium ion. Similar results were noted when zeolites were added directly to cattle feedlots, suggesting that not only can healthier and less odoriferous environments be achieved by the addition of zeolites to animal manure, but that the nitrogen-retention ability of the manure can be improved as well.

Zeolite purification of low-Btu methane produced by the anaerobic fermentation of excrement and other agricultural waste products may be a means of producing inexpensive energy on individual farms or in small communities, and zeolite ion-exchange processes may be employed in the removal of ammonium ions from recirculating or closed aquacultural systems, thereby allowing more fish to be raised or transported in the same volume of water. Aquacultural research of this type has been or is being conducted by Becker Industries, Newport, OR; the U.S. Fish and Wildlife Service, Fish Cultural Development Center, Bozeman, MT; Jungle Laboratories, Comfort, TX; the Department of Fisheries and Wildlife, New Mexico State University, Las Crucas, NM; the Narragansett Marine Laboratory, University of Rhode Island, Kingston, RI; and the Department of Zoology, Southern Illinois University, Carbondale, IL.

CONCLUSIONS AND RECOMMENDATIONS

Although they have been used locally for several years in Japan and other parts of the Far East in small amounts, the use of zeolites as soil amendments, fertilizer supplements, additives to animal rations, and in the treatment of agricultural wastes is still in the experimental stage in the United States. A number of agricultural organizations have or are investigat-

ing such uses for natural zeolites in this country. The projects have generally been sponsored by grants or contracts from companies that themselves are developing applications for zeolites in one or more areas of technology, or they have been funded by the institutions themselves and make use of zeolite products provided free or at low cost by the companies. Table 19 summarizes the agricultural research efforts of companies that hold properties of natural zeolites. In addition, other, nonproperty holding organizations, such as International Minerals & Chemical Corp., Cargill, Inc., and Lowe's, Inc., have also been involved in the development of uses of natural zeolites in agriculture.

Overseas, six to eight agricultural stations in Japan continue to investigate natural zeolites as soil amendments and dietary supplements; Pratley Perlite Mining Co., which owns a large clinoptilolite deposit in South Africa, has made several studies of the use of zeolites in the rations of swine and poultry; and a recent Bulgarian-Soviet symposium[2] on natural zeolites contained seven papers on animal-nutrition applications and two on soil-amendment uses.

[2]Second Bulgarian-Soviet Symposium on Natural Zeolites, Kardzhali, Bulgaria, Oct. 11-14, 1979.

Similar projects are in progress in Cuba and Hungary, where deposits of clinoptilolite and mordenite are abundant. The intense interest in the several socialistic countries mentioned above undoubtedly stems from their efforts to use their own natural resources and thereby reduce their dependency on foreign sources of expensive fertilizers and animal rations. These same objectives, of course, are desired by each developing nation—maximum use of local raw materials and minimal use of imported products that must be purchased with hard currency. Where they can be found within a particular nation or where they can be obtained from neighboring countries at minimum cost, natural zeolites have the potential to increase the agricultural productivity of that nation by reducing the need for or increasing the efficiency of chemical fertilizers and animal feedstuffs.

To convert the agricultural promise of natural zeolites into commercial reality, a concerted effort must be made in the United States and elsewhere by both the private sector and by State and Federal funding organizations. The studies to date have been mainly of a preliminary nature—radishes have been grown instead of potatoes, and rats have been raised instead of beef cattle—or of limited duration or extent.

Table 19.—Zeolite Property Holders and Zeoagricultural Research Efforts

Organization	Zeolite Species[a]	Research Effort
Anaconda Company	Clinoptilolite, Erionite, Chabazite/Erionite, *Clinoptilolite, Chabazite, Mordenite, Phillipsite*	In-house; sponsored
Colorado Lien Co.	Clinoptilolite	Sponsored
Double Eagle Petroleum & Mining Co.	Clinoptilolite, *Clinoptilolite*	Sponsored
Forminco	*Clinoptilolite*	None
Harris & Western Corp.	*Clinoptilolite/Mordenite*	None
Ladd Mountain Mining Co.	*Erionite/Clinoptilolite*	None
Leonard Resources	*Clinoptilolite*	Sponsored
Letcher Associates	*Clinoptilolite*	None
Minerals Research	*Phillipsite*	None
Minobras, Inc.	*Erionite*	None
Mobil Oil Corp.	Erionite	None
Monolith Portland Cement Co.	Clinoptilolite	None
NL Industries	Clinoptilolite	None
Norton Co.	Chabazite/Erionite, *Ferrierite*	None
NRG Corp.	Chabazite/Erionite	None
Occidental Minerals Corp.	Clinoptilolite, *Clinoptilolite, Erionite*	In-house; sponsored
Rocky Mountain Energy Co.	Clinoptilolite	Sponsored
Union Carbide Corp.	Chabazite/Erionite, Mordenite, Erionite	In-house; sponsored
U.S. Energy Corp.	*Clinoptilolite*	None
W. R. Grace & Co.	Chabazite/Erionite, *Ferrierite*	None

[a]Roman type = working mines; italics = prospects.

Little information has been developed to illuminate the long-term benefits or adverse impacts on food production. Many of the companies sponsoring this research have considered the results proprietary, and rightfully so, but workers in the field are therefore unable to obtain the latest information, a situation that often results in massive duplication of effort. Large-scale testing of zeolites under sustained field conditions and projects involving statistically significant numbers of animals are greatly needed at this juncture. Such projects will require continuous funding by State and Federal agencies, or perhaps, international agencies if the results are to be applied to developing nations. It would be extremely instructive to carry out such testing in several developing nations themselves, where agricultural practices are not as finely tuned as in the United States.

The actual introduction of natural zeolites into specific agricultural processes should pose no major problems. Crushed and sized material could be added to the fields directly or banded into the soil either alone or with normal fertilizers using standard equipment. Likewise, the zeolite could be mixed as a powder or fine granules with normal feedstuffs provided for livestock, or be inserted as a bolus into the stomachs of ruminants. It could also be sprinkled on or mixed with manure accumulations on a daily basis for nutrient retentivity.

None of these processes would require special machinery; in fact, all could be carried out by hand, if such were the common practice in that country. Users would, of course, need to be instructed as to the correct amount to apply to fields or to mix with normal rations, and the optimum time to apply it for specific crops, and considerable educational efforts may be necessary to convince the small farmer of the benefits of zeolite additives. In this regard, zeolites are no different than any innovative procedure that many farmers are slow to accept.

Because the use of zeolites in agricultural processes has not yet reached the proven or commercial stage, any scenario developed to introduce this promising technology into developing nations would involve contributions from both the United States and the developing nations. The contribution of the United States would be both geological and agricultural expertise in zeolite technology, whereas the contribution of the developing nations would be a willingness to search for deposits of zeolites and a willingness to carry out some necessary long-term or large-scale testing under field conditions. Any implementation plan should begin with a series of visits by a team of zeolite experts from the United States to selected developing nations in the world where zeolites are known or have a high probability of occurring. In addition to a leader who would have a broad background in zeolite technology, the team would consist of four to eight geologists, agronomists, animal nutritionists, and agricultural engineers who are not only experienced in the use of zeolites in agriculture or in the occurrence of zeolites in volcanogenic sedimentary formations, but who can incite an enthusiasm in others for the wonderful things that zeolites can do. The team would include:

- a geologist who is not only knowledgeable about the occurrence of zeolites in such environments, but who is capable of working with local resource people to find and evaluate potential deposits of zeolites in these countries;
- an agronomist or plant scientist with considerable experience in the use of zeolites to improve crop productivity;
- an animal nutritionist with the necessary expertise in the use of zeolites as dietary supplements in animal nutrition; and
- an agricultural engineer who has worked with zeolites in excrement treatment to improve the health of confined livestock or the ammonium retentivity of animal wastes. The agricultural engineer would also provide practical experience to the team.

Prior to the first visit to a developing nation, the team would arm itself with the latest information in the field by visiting the leading experiment stations and research laboratories in this country and abroad where zeoagricultural investigations are being carried out. Special emphasis would be placed on the recent work in Japan and in countries of Eastern Europe.

Each visit would be for a 10-day period, wherein the first 2 days would be spent in the company of local geologists and/or agronomists examining the general terrain of the country and gaining a brief impression of the geology and the agricultural conditions. A third day would be devoted to a series of talks by each of the team members on his specialty before an audience of local geologists, agriculturalists, government officials, labor union leaders, and bureaucrats and anyone else who would be interested in finding out about this new technology. During the next several days the team would split into small groups for individual consultations in the field with local technical people responsible for the implementation of the technology. The geologists would, perhaps, visit suspected areas of zeolite formations, whereas the agronomist could inspect potential sites for study, providing samples of zeolite for initial investigation. The last day of each visit would be devoted to round table discussions by local agricultural experts, geologists, and team members to determine what had been accomplished and the next steps to take.

It is vital that the introduction of zeoagriculture into a developing nation not end with the visit of a team of U.S. experts. On the contrary, the initial visit should be followed up as soon as possible with specific plans for implementing the technology into the nation's agricultural processes. Although the implementation scenario of all innovative technologies would appear to be similar from this point on, the zeolite scenario would involve a search for these materials in the developing nation if such materials had not already been reported from that country. Such exploration would probably be carried out by the local geological survey or mining agency, but should be assisted in the field by a geologist familiar with the occurrence of zeolites. If zeolites are known in the country or if they can be obtained from neighboring regions without difficulty, plans should be made with the country's agricultural people to field test the technology under optimum conditions. Such plans and tests should also be made with the assistance of agronomists or animal scientists already familiar with the use of zeolites in these processes.

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Chapter IX

Agrotechnologies Based on Symbiotic Systems That Fix Nitrogen

Jake Halliday

Contents

	Page
Abstract	161
Introduction	162
The Biological Nitrogen Fixation (BNF) Process	163
Agrotechnologies Based on BNF by Legumes	163
The Use of Legumes	164
Inoculant Technology	164
Current Use of Legume-Based BNF Technology	168
The Use of Legumes	168
Inoculant Technology	168
How BNF by Legumes Increases Crop Yields and Soil Fertility	169
Future Potential of Legume-Based BNF Technology	172
Constraints on Implementation of BNF Technology	173
Scenario for Full Implementation of BNF Technology	176
References	179
Acronyms	182

Table

Table No.	*Page*
1. Allocating Funds for a BNF Resource Center	179

Figure

Figure No.	*Page*
1. Pathways for Flow of Nitrogen From Legumes to Other Crops	170

Chapter IX

Agrotechnologies Based on Symbiotic Systems That Fix Nitrogen

ABSTRACT

When sustained productivity is sought from low-input farming systems, legume crops are especially attractive because of their ability to be self-sufficient for nitrogen supply. Life on Earth is dependent on transformations of atmospheric nitrogen to a form that can be absorbed from the soil by plants and used in protein synthesis. The process can be accomplished industrially, but at a very high energy cost. Biological nitrogen fixation (BNF) by symbiotic associations of plants with micro-organisms is more sound economically and environmentally than using nitrogen fertilizer in agriculture.

Agrotechnology based on BNF by legumes has two facets: the use of legumes and the use of inoculant technology. Currently, legumes are used in many systems without any specific attempt to maximize their nitrogen fixation through inoculant technology. But yields can be increased and nitrogen fertilizer requirements reduced by using appropriate inoculant technology. Maximum gains from BNF in agriculture will arise from innovative use of legumes in areas and in roles they have not occupied previously, provided that their nodulation and nitrogen fixation is assured. Most legumes in the Tropics "fix" about 100 kg/ha/year of nitrogen. The common forage tree leucaena fixes around 350 kg/ha/year and the potential for some species is as high as 800 kg/ha/year. Fertilizer savings represent not only significant savings in foreign exchange, but also reduced dependence on the oil-rich nations whose influence over the cost and availability of nitrogen fertilizer is increasing.

The use of legumes involves the management of legume species in farming systems not only for direct benefits accruing from the multiple uses of legume products and the greater stability of mixed-cropping, but also for indirect benefits arising from their ability in some circumstances to make a net contribution of nitrogen to the soil. This provides nitrogen for companion or later nonleguminous crops.

The objective of inoculant technology is to introduce sufficiently high numbers of preselected strains of rhizobia that they have a competitive advantage over any indigenous soil strains of lesser nitrogen-fixing ability into the vicinity of the emerging root. Inoculation technology involves: selecting strains of rhizobia that are compatible and effective nitrogen-fixers with particular legumes; multiplying selected strains to high population densities in bulk cultures; incorporating the liquid rhizobial cultures into a carrier material (usually finely milled peat) for packaging and distribution; and finally, coating the seeds of legumes with the carrier or implanting the soil with the inoculant.

Legumes already are used widely and consistently, though as minor crops, in farming systems of the Tropics. Inoculant technology is used on a meaningful scale only in a few countries other than the United States and Australia. Great future potential rests in the development of:

- legume-based pastures and viable multiple-cropping systems including legumes for under-used savannahs;
- agroforestry systems that combine fast-growing, nitrogen-fixing trees, legumes, and other crops to meet the food and fuel requirements of the rural poor;
- fast-growing leguminous trees for reforesting water catchment areas following forest clearance;

- legume-based cropping systems to give sustained productivity in cleared jungle soils which typically exhibit a rapid decline in fertility under conventional cropping; and
- selection of deep-rooted, drought-tolerant leguminous trees that can serve as browse species in the world's dry lands.

The major constraints to full implementation of legume-based BNF technology in the Tropics relate to the delivery and acceptability of the technology at the farm level. The constraints are political, cultural, socioeconomic and, to a lesser extent, scientific. The major scientific constraint is inadequate understanding of host legume, rhizobial strain, and environment interactions. This results in an inability to predict whether a given legume will respond to inoculation in a particular region or not. A constraint on better understanding of these interactions is the lack of trained personnel to execute legume inoculation trials to determine the economic benefits. A lack of domestic inoculant production plants also constrains research, development, and production enterprises.

Legume-based BNF technology would benefit from:

- increasing economic and political pressure for greater energy efficiency in agriculture;
- increased recognition by decisionmakers in funding agencies and in governments of the potentials for exploiting BNF in developing country agriculture;
- an increase in trained professionals and technicians in tropical countries;
- improved integration of legume germplasm improvement programs and legume bacteriology programs;
- concerted application of international funding to establish a BNF Resource Center (this Center could be staffed, equipped, and budgeted to provide technical assistance; offer germplasm and information services; provide professional and technical training; conduct research necessary to adapt BNF technology to individual developing countries when it is beyond the capability of local researchers);
- improved opportunity to exchange findings from field research programs; and
- implementation of a sequence of standardized experiments designed to quantify the economic yield benefit attributable to legume inoculation under field conditions and followed by studies to quantify the nitrogen balance in multiple cropping systems that include legumes.

Legume inoculation does not substantially affect the need for farm labor. The inoculation is accomplished as an integral part of the sowing method whether by hand or mechanized planter. If fertilizers are normally applied, elimination of the need for nitrogen reduces the capital cost but no substantial labor saving is realized as other fertilizers still need to be applied. The use of legumes to benefit companion or following crops is consistent with the farming systems already prevalent in the Tropics. To use legume-fixed nitrogen for, as an example, cereal production in the United States would necessitate adoption of mixed-cropping systems that are not easily mechanized. Thus, an increased demand for labor would be an impact. The major positive impacts of BNF technology are indirect through elimination of the multitude of negative environmental impacts associated with nitrogen fertilizer production, distribution, and use in agriculture.

INTRODUCTION

Beans and peas are well-known examples of food products from the array of plant species that belong to the legume family. Legumes are especially attractive when sustained productivity is sought from low-input farming systems. This is because of their unusual ability to be self-sufficient for nitrogen supply.

Nitrogen is an essential component of all life forms; it is a cornerstone in the chemical struc-

ture of proteins. Ironically, nitrogen is abundant in the atmosphere—the air we breathe is 80 percent nitrogen. In its gaseous form, however, nitrogen occurs as dinitrogen molecules, each having two nitrogen atoms joined by a triple bond. This is among the most stable, inert molecules known and cannot be used directly. Thus, life on Earth is totally dependent on transformations of atmospheric nitrogen to a form in which it can be use readily by plants, and subsequently, by animals and man.

This process is referred to as "nitrogen fixation" and involves splitting dinitrogen into two nitrogen atoms that are then reacted with hydrogen (generated by splitting water molecules) to form first ammonia and subsequently a range of nitrogenous compounds. Nitrogen fixation can be accomplished industrially, but the process is one of the most energy demanding in today's agriculture. The energy cost of fixing nitrogen in the form of urea, ammonium sulfate, or ammonium nitrate is compounded by the additional costs involved in transport and application. Additionally, the rather small proportion of nitrogen-fertilizer actually taken up by the crop to which it is applied and the serious environmental pollution that can be caused by nitrogen lost from agricultural land through run-off are incentives for appraising alternate nitrogen-sources. Self-sufficiency for nitrogen supply as exemplified by the legumes is thus a highly desirable trait.

THE BIOLOGICAL NITROGEN FIXATION (BNF) PROCESS

Biological nitrogen fixation (BNF) in legumes is possibly because of the mutually beneficial association (symbiosis) that can form between leguminous plants and certain micro-organisms from a specific family of soil bacteria known as Rhizobium. Rhizobia can penetrate the roots of legumes and give rise to highly specialized organs referred to as root nodules. These are quite different from tumors or other swellings that commonly occur on plant roots as a result of infection by disease-causing (pathogenic) organisms. The structure and function of nodulated legumes is modified in such a way that carbohydrates (sugars) produced in the leaves of the plant during photosynthesis are delivered to the nodulated root where they are respired to provide energy. In the nodules, this energy is consumed during nitrogen fixation and it is used to sustain the growth requirements of the rhizobia.

Gaseous dinitrogen enters the nodule from the air spaces in the surrounding soil. An enzyme, nitrogenase, that is the unique contribution of the microsymbiont, catalyzes the splitting of dinitrogen molecules and the reaction of their component atoms to form ammonia. Neither the sequence of reactions and transformations that follow initial fixation nor the precise sites in the nodule where the events occur are fully understood. The steps involve very rapid incorporation of ammonia, which would ordinarily be toxic to both symbionts, into nitrogenous compounds such as amino acids, amides, and/or ureides depending on the particular legume species. These are used throughout the plant as building blocks for plant proteins.

AGROTECHNOLOGIES BASED ON BNF BY LEGUMES

Most farmers in the Tropics do not know that legumes fix nitrogen. Yet, traditional and modern farming systems of the Tropics almost invariably include legumes (52,59). Thus, legume cultivation happens because farmers over many centuries have recognized that legumes

are valuable components in farming systems rather than from intentional exploitation of biological nitrogen fixation per se.

Agrotechnology based on BNF by legumes, therefore, has two major aspects. One relates to the deliberate inclusion of legumes in cropping systems to derive benefits from their nitrogen fixation. The other concerns the intentional use of specific practices to maximize nitrogen fixation by legumes. For convenience these two facets of BNF technology will be referred to as "use of legumes" and "inoculation technology." The distinction is drawn to emphasize that currently legumes are used widely with less than maximal benefits because of deficient symbiotic associations. Productivity could be increased by using appropriate technology to assure effective symbiotic nitrogen fixation by legumes. Much greater gains in productivity and economies of energy can be realized from reduced fertilizer requirements through innovative use of legumes in roles they have not occupied previously in production systems (e.g., the use of fast-growing leguminous trees in agroforestry systems). Production gains will be greatest if the use of legumes is always complemented by appropriate inoculant technology. This is because legumes can only benefit fully from biological nitrogen fixation if they encounter rhizobia with which they are genetically compatible.

THE USE OF LEGUMES

The benefits from BNF through the use of legumes in farming systems are both direct, because the legume has an intrinsic value, and indirect, because inclusion of a legume affords greater yield stability in adverse growth conditions and can benefit companion or following nonleguminous crops.

Direct benefits from BNF by legumes in cropping systems arise from the multiple uses of plants in the legume family. Though known primarily for grain, forage, or feed production, legumes are also cultivated in the Tropics for timber, fuelwood, green manures, oils, fibers, gums, drugs, dyes, and resins. Additionally, they may be used as hedges; ground covers for weed, insect, and disease control; as soil stabilizers on terraced slopes; or simply for shade or as ornamentals (59).

Indirect benefits accrue from the stability of performance and assurance of some economic return for at least one component under unfavorable conditions when legumes are intercropped with other crops. Stability is afforded, for example, in erratic rainfall zones when the components in the intercropping system are separated in time such as with sorghum/pigeon pea and groundnut/cotton (59,56). When there is an outbreak of pests or diseases, maize/beans and other intercrops afford stability of yields and income (3,32). Other indirect benefits accrue from the ability of legumes to make a net contribution of nitrogen to the soil under some circumstances, thereby reducing the nitrogen-fertilizer requirements for a companion or following nonleguminous crop.

INOCULANT TECHNOLOGY

There is a commonly held view (2) that tropical legumes are much more promiscuous than temperate legumes—that they nodulate freely with a wide range of tropical rhizobia and that tropical soils are laden with so many bacteria that effective nodulation is virtually guaranteed without inoculation (49,30). This view is no longer well-founded. Some species and accessions from genera previously considered to be promiscuous (2) require specific strains of *Rhizobium* (9,28,26) or form highly effective symbioses with only a few out of the wide ar-

ray of strains with which they nodulate (69, 16,22). Recent intensification of interest in the tropical legumes and their rhizobia is revealing much greater variation in genetic compatibility and nitrogen fixation effectiveness than has generally been acknowledged (38,23). A plea has been made for recognition that tropical legumes fall into one of three categories (23).

- *Promiscuous effective (PE) group*, where nodulation occurs with a wide array of rhizobia isolated from many legume genera and the resultant symbioses are predominantly effective in nitrogen fixation.
- *Promiscuous ineffective (PI) group*, where nodulation occurs with an array of strains of rhizobia isolated from many legume genera, but where fully effective symbioses form with only a few of those strains.
- *Specific (S) group*, where those strains from the same genus (or a restricted number of other genera) form effective symbioses.

Just as with the temperate legumes, the likelihood that compatible, effective rhizobia will not always be present in sufficient numbers in the soil microflora is the rationale for using inoculation technology for tropical legumes (24). When a tropical legume seed is sown uninoculated in a tropical soil, a native rhizobial population of strains differing greatly in their symbiotic effectiveness compete for the finite number of nodulation sites on the legume roots. Many forage legumes bear only 10 to 20 nodules on which they depend for nitrogen during the first three months of their establishment. Thus it becomes critically important that each of the nodules that form on the root contain a strain of *Rhizobium* that is fully effective in fixing nitrogen. The underlying objective in inoculation technology is to introduce sufficiently high numbers of preselected strains of rhizobia into the vicinity of the emerging root that they have a competitive advantage over any indigenous soil strains of lesser nitrogen-fixing ability in the formation of root-nodules.

Inoculation technology involves:

- selecting strains of rhizobia that are compatible and effective nitrogen-fixers with particular legumes;
- multiplying selected strains to high population densities in bulk cultures;
- incorporating the liquid rhizobial cultures into a carrier material (usually finely milled peat) for packaging and distribution; and
- finally, coating the seeds of legumes with the carrier or implanting the soil with the inoculant directly into the seed drill (64, 14,25).

An inoculum strain of *Rhizobium* recommended for a particular host must be able to form effective nitrogen-fixing nodules with that host under a wide range of field conditions. Nitrogen fixation effectiveness is only one important criterion for an inoculant strain. Other criteria include: competitiveness in nodule formation, particularly against less effective strains; persistence in the soil in the absence of the host, especially for strains for annual species; promptness to form nodules; ability to fix nitrogen under a range of soil temperature conditions; tolerance to pesticides; tolerance of low soil pH; nodulation in the presence of high levels of soil nitrogen; and ability to grow and survive in peat inoculants.

The host genotype interacts with the infecting strain of *Rhizobium* in determining the level of nitrogen fixation, with the host playing the dominant role. Thus, two sources of variation (plant and *Rhizobium* strain) can be exploited in selection programs. Most commonly, though, the plant is selected independently and a suitable strain sought thereafter, thus allowing only for exploitation of strain variability. The range of specificities of host genotype interactions is well-illustrated by soybean (77) and in the African clovers (51).

Three approaches to select strains for inoculants exist: select numerous inoculants, each with a highly effective strain for individual species; select "wide-spectrum" strains that vary

from good to excellent in nitrogen fixation with a range of legumes; or select multiple-strain inoculants containing the best strain for each host species. There may be a conflict between the option that would be chosen for commercial expediency and that which is scientifically preferred (25). In Australia, "wide-spectrum" strains are used when these are available, but there is increasing use of specialized inoculants with specific strains for individual hosts. Despite findings that suggest that multi-strain inoculant should be avoided because of possible antagonistic and competitive effects (46) and competition in nodule formation from the less effective strains (17) this is the approach used successfully by the U.S. inoculant industry.

Strains for testing can be obtained from other laboratories working with the same species, from nodules on plants in the native habitat from which they were originally collected, and from nodules formed on the legume by native strains after sowing uninoculated seed in the region where the new species is expected to be used. None of these sources is invariably better in screening programs.

Most legume inoculants are prepared by adding liquid cultures of rhizobium to a finely ground carrier base material such as peat. Although mixtures of peat with soil or compost mixtures, lignite, coir dust, and some other organic materials have been used, peat has proven to be the most acceptable carrier worldwide. Agar, broth, and lyophylized cultures are not recommended because survival rates for these forms are poor (20,21,72).

Peat cultures can be prepared in two ways. Either ground (milled) peat is mixed with a high viable count (more than 10^9 rhizobia/ml) broth culture in sufficient volume to provide the minimum number of rhizobium acceptable for use, or sterilized peat is inoculated with a small volume of culture and incubated to allow multiplication of the rhizobia. The choice of method will depend on two factors—the survival of the rhizobia in peat in numbers high enough to meet a minimum standard of quality, and the availability of suitable, sterilizable containers and sterilizing facilities. The two factors that most affect survival of rhizobia in peat are temperature of storage and sterility of the peat. There are differences among species and also between strains of the same species of *Rhizobium* in their ability to survive well in peat (63).

Like all biological products, legume inoculants are prone to loss of quality because of variation in the organism and from unforeseen factors affecting some aspect of growth or survival. It is therefore essential that a quality control system be established. In Australia, large-scale manufacture of legume inoculants is by private enterprise and a separate, official (government) control laboratory is responsible for maintaining a high-quality product. The control laboratory maintains and supplies recommended strains of *Rhizobium* to the industry, checks strains annually for ability to fix nitrogen, assesses quality of cultures during and after manufacture, and conducts any research that is necessary to overcome problems associated with production and survival. In the United States, the industry is free to select its own strains and official control ensures that the product can form nodules on the legume for which it is recommended.

Although control of inoculant quality is primarily in the manufacturer's interest and therefore his responsibility, control by external bodies provides protection from less scrupulous operators and genuine failure of a strain outside manufacturer control. Not all countries back their control labs with legislation. A control group requires suitably qualified and experienced personnel with facilities to permit normal aseptic culture transfer and plant growth facilities suitable for legumes from many environments. Methods of assessment involve both qualitative and quantitative tests. The number and extent of these may vary according to competence and experience of manufacturers and the standards desired. In Australia, this control extends to holding stocks of the strains used in inoculants. This is not the case in the United States (29,70). In addition to assessment of quality throughout manufacture, it is important to monitor product quality in retail outlets. Standards acceptable at this

level may vary between countries. It is important that standards be realistic and within the capability of manufacturers yet ensure that sufficient viable rhizobia are applied to the seed to provide a satisfactory inoculation. In many instances this can be as few as 100 rhizobia per seed but in cases of severe environmental stress as high as 10,000 or even 500,000 (11,12,21).

The prime objective of inoculation of legume seed with rhizobial inoculants is to induce nodulation of the introduced legume host plant. Rhizobia introduced into new environments must live saprophytically in competition with other rhizobia and soil micro-organisms in an environment that may be adverse for their growth and survival until the host seedling roots provide the ecological niche to which they are adapted. Thus, steps should be taken to help inoculant strains: remain viable until the host seedling is at the susceptible stage for infection; compete with any natural rhizobia for infection sites on the roots of the host legume and permit maximum nitrogen fixation; nodulate its host promptly and effectively over a range of environmental conditions; and persist in the soil for at least several years in sufficient numbers to maintain nodulation of perennial legumes or to achieve prompt nodulation of regenerating annual species.

The first attempts at inoculation involved transferring soil from one field to the next, but when the organisms responsible for nodule formation were isolated, artificial cultures soon replaced the laborious soil transfer technique. The usual inoculation technique is to apply the inoculant to the seed just before sowing either as a dust or as a slurry with water or adhesive solution. Adhesives such as gum arabic or celluloses not only ensure that all the inoculum adheres to the seed but also provides a more favorable environment for survival of the inoculum. Pelleting of seed with finely ground coating materials such as lime, bentonite, rock phosphate, and even bauxite (11,12) have been used to protect rhizobia during their time on the seed coat. Pelleting is a simple on-farm technique (11,50) but custom-pelleted (by seedsmen at farmer's request) and preinoculated seed is now more popular. This latter procedure is potentially able to provide high populations of rhizobia on the seed for a long period of time (one growing season to the next) but has not yet been fully developed or exploited.

Most preinoculation procedures are based on multiple coatings, alternately of adhesive and finely ground pelleting materials as used in simple pelleting. The peat inoculant is included as one (or more) of these coating layers. Soaking seeds in a broth suspension and then exposing them to either high pressure or vacuum to impregnate the rhizobia into or below the seed coat has not proven successful. Theoretically, rhizobia introduced in this way would be protected from drying and other adverse environmental conditions, but the quality of products produced commercially has been variable to very poor (16,10,66). It is, in fact, an indictment of the research workers in this area that 25 years has yielded so little progress in an area where there is so much potential.

These production techniques are particularly applicable to less well-developed and inexperienced rural groups. If high-quality and reliable products were marketed by a manufacturer or seeds distributor, the farmer would not need to be involved in legume inoculation.

A recent alternative to pelleting and preinoculation has been the use of concentrated liquid or solid granular peat culture that can be sprayed or drilled directly into the soil with the seed during planting. Suspensions of rhizobia either as reconstituted frozen concentrates or suspensions of peat inoculant can be applied with conventional equipment. Similarly, granulated peat inoculants can be drilled in from separate hoppers on the drilling equipment. These methods have been especially successful for introducing inoculant strains into situations where there are large populations of competing naturally occurring soil rhizobia (6), in cases of adverse conditions such as hot-dry soils (68), and where insecticide or fungicide seed treatment precludes direct seed inoculation (67,12). Solid inoculant, also known as granular or "soil implant" inoculum, is advantageous also, where seeding rates for crop legumes of 70 to 100 kg/ha make on-the-farm inoculation logistically impracticable.

CURRENT USE OF LEGUME-BASED BNF TECHNOLOGY

The Use of Legumes

Grain legumes are cultivated widely in a variety of agro-climatic zones in the Tropics and Subtropics. Total area in grain legumes in 1979 was 175 billion hectares. Dry bean (*Phaseolus vulgaris*) is the most important grain legume in Latin America, groundnut (*Arachis hypogaea*) in Africa and collectively groundnut, piegeon pea (*Cajanus cajan*) and chickpea (*Cicer arietinum*) in Asia. These and other grain legumes have been consistent components of human diet in the Tropics for centuries, yet in quantitative terms they continue to be minor crops.

The use of legumes in mixed legume/grass pastures in the Tropics is at present restricted to northern Australia, the United States (Hawaii, Florida), southern Brazil, and northeastern Argentina. The total area in improved legume/grass pasture is insignificant compared to the area of native grasslands under grazing. The use of temperate forage legumes in mixed pastures at high altitude locations in developing countries is frequent but is outside the scope of this report.

Production statistics for tropical grain legumes are seldom accurate. Most of the production is on a subsistence scale on small farms and the yields are seldom included in official statistics. Thus, a figure of 186 million tons (31) should be regarded as an understatement.

There are many agencies supporting and conducting research related to the use of legumes. International agencies such as FAO, UNDP, IBPGR, and the IARCs all have grain and forage legume programs. USAID, together with the governmental agencies of many countries, engaged in foreign agricultural development support research on legumes. The World Bank and several private and public foundations also support legume research. The author is not aware of any country in the Tropics that does not have a legume project within its official agricultural program. Additionally, universities and agricultural colleges in tropical countries usually have legume programs. These projects cover the physiology, plant nutrition, agronomy, pathology, entomology, breeding, and seed production of legume crops. Insofar as BNF proceeds at a rate governed strongly by the plant's ability to deliver carbohydrate to its root nodules, most technologies that improve overall plant performance are likely to have a beneficial impact on nodulation and nitrogen fixation. Relatively few projects, however, give adequate attention to specific techniques for maximizing BNF by the respective legume. In fact, some research programs with legumes are conducted under nitrogen-fertilized conditions or in fertile, nitrogen-rich soils. Breeding for high-yielding varieties under such conditions has resulted in plant types that are only weakly symbiotic and heavily dependent on soil nitrogen.

Given the important role of grain legumes as the major dietary protein source for low-income groups in the developing countries, it is hardly surprising that such a multitude of funding agencies and implementing organizations give attention to research on legume technology. While it is to be expected that there will be overall gains in the amount of nitrogen fixed from improved performance by legumes in the roles, and on the acreage they currently occupy, the major gains in BNF will follow increases in the total land area where legumes are grown and especially the innovative use of hitherto underutilized legumes.

Inoculant Technology

Inoculant technology is used widely on a commercial scale in the developed countries. The United States and Australia have substantial industries to produce, distribute, and market legume inoculants. There is also commercial-scale production in Brazil, Uruguay, Argentina, India, and Egypt. Inoculants are available commercially in many other countries but they are produced in U.S. or Australian laboratories. Some research centers, such as CIAT and the University of Hawaii NifTAL Project, produce inoculants in pilot-scale plants

as a service to researchers and occasionally to legume growers. Demands for inoculation technology are increasing, primarily because of the increased use of soybeans.

There are dangers in trying to satisfy this demand by importing inoculants developed in the United States or elsewhere. This is because present inoculation technology has not proven transferable. That is, strains of *Rhizobium* and inoculation methods developed for conditions at one location in a particular farming system do not perform equally well at another location in a different farming system. Furthermore, the viability of rhizobia in legume inoculants is greatly affected by storage conditions during shipment. Since producers are unable to control such factors, no guarantee can be given that the inoculants are of merchantable quality on arrival at their destination. For both these reasons inoculation failures are a common occurrence and this is harming consumer acceptance of the technology. An ideal scenario for improved implementation of BNF technology is described in a later section.

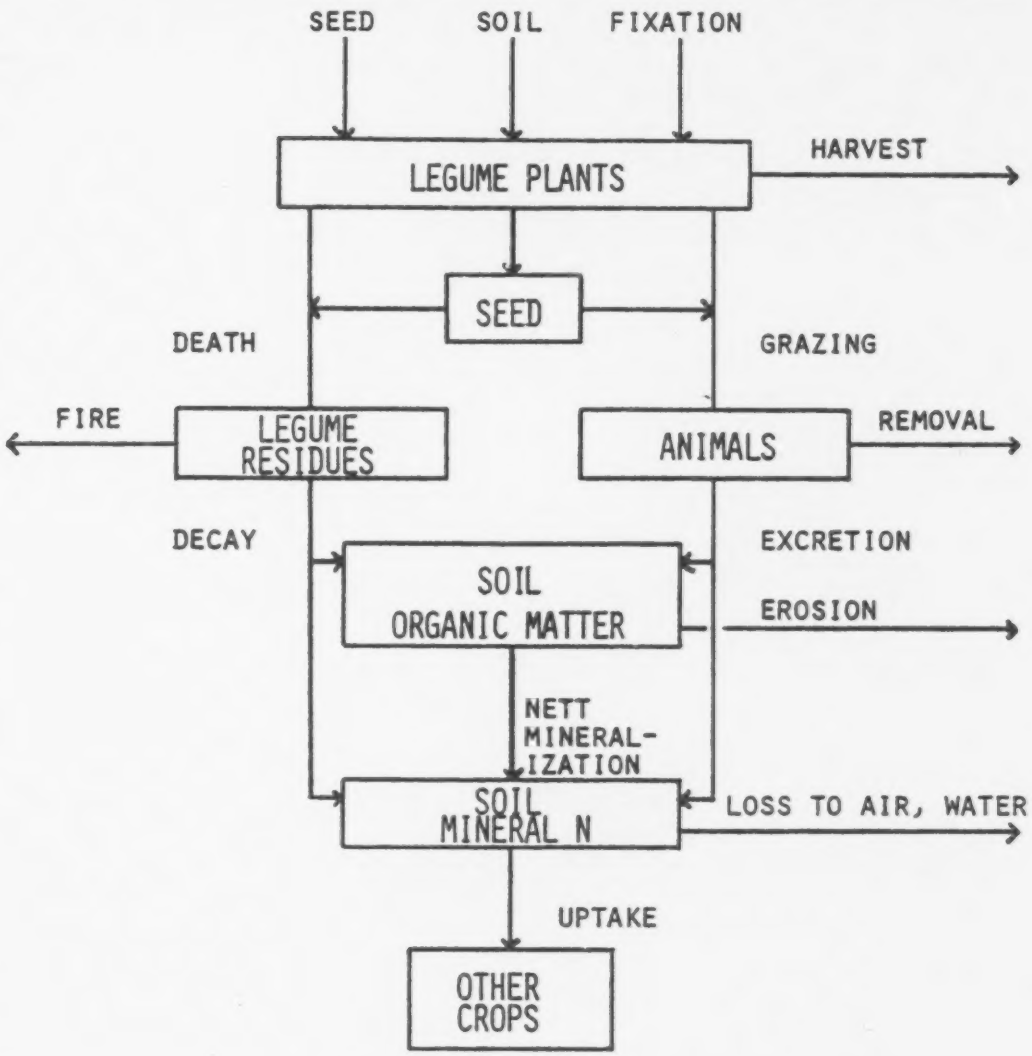
The organizations funding research to adapt inoculant technology to the circumstances where it will be used in tropical countries include: UNDP by its support to the IARCs through CGIAR and for a specific research program involving IITA and BTI/Cornell University; UNEP and UNESCO support inoculant technology under the MIRCEN Project; FAO is actively considering the role it might play in the adaptation of inoculant technology for use in developing country agriculture; USAID through its contracts with University of Hawaii (NifTAL Project) and USDA, Beltsville ARC (World Rhizobium Study and Collection Center) through grants under Section 211(d) to the U.S. Universities' Consortium on BNF in the Tropics, and through a portfolio of small grants administered by USDA SEA/CR; USAID and several governmental and nongovernmental agencies that support the CGIAR are thereby sponsoring work at CIAT, IITA, ICRISAT, and ICARDA on the adaptation of inoculant technology for use in the Tropics.

HOW BNF BY LEGUMES INCREASES CROP YIELDS AND SOIL FERTILITY

Consider the possible pathways to transfer nitrogen from legumes to other crops (figure 1). The relative importance of the transfer pathways of nitrogen from legumes to other crops and/or the soil can be estimated. Nitrogen gains per hectare per year entering the cycle as seeds (1 to 2 kg) (41) and in acid rainfall (1.5 to 3.5 kg) (78) are small compared to the nitrogen fixed biologically. About 50 percent of the nitrogen accumulated in legumes in fertile soils is attributed to BNF (71), though the proportion from fixed nitrogen will be greater in impoverished soils and lesser under nitrogen fertilization. Nitrogen accumulation in legume monocrops ranges from 50 to 350 kg/ha/year. It is generally accepted that nitrogen fixation of around 100 kg/ha can be expected from the majority of grain and forage legumes. Higher levels are possible for leucaena and other forage legumes with a 12-month growing season. Low levels are likely for bad nitrogen fixers with short growing seasons (e.g., *Phaseolus vulgaris*).

As an example, follow the fate of 100 kg of biologically fixed nitrogen entering the cycle. Between 60 and 90 percent of the nitrogen accumulated in legumes is removed as grain—depending on the species, harvest index, and harvesting practice, or as animal products depending on the intensity and selectivity of grazing. Thus, in an intercropping system only 10 to 40 kg nitrogen could potentially benefit other crops. Some of the organic nitrogen of the legume residues is mineralized rapidly. The rest is added to the soil organic matter pool and it

Figure 1.—Pathways for Flow of Nitrogen From Legumes to Other Crops (from Henzell, 1977)



is mineralized slowly over a much longer period. Studies show that 60 percent is probably the maximum portion of the nitrogen in the organic residue of a legume crop that could be mineralized in time to benefit a following crop.

If 50 percent of the nitrogen is used in the initial mineralization, in a cropping system where the legume fixes 100 kg/ha/year only 5 to 20 kg of nitrogen is likely to benefit the following crop. One practice that could substantially increase the contribution is green manuring. If one year's production were incorporated into the soil, it would leave a residual benefit of 50 kg/ha/year for the following crop. Experience has shown, however, that crops do not necessarily respond to exaggerated applications of green manures.

There are few farming systems where green manuring is economically feasible (41,8) since land is tied up without immediate economic

return. Where green manuring is practiced, 5 tons of green matter per hectare is an accepted application rate (54). This would represent an addition of only 40 kg/ha of nitrogen to the soil, of which only about 20 kg would mineralize to the benefit of the crop. Green gram contributed 22 kg of nitrogen to following crops and calapo/stylo green manure contributed 15 kg (1).

The situation is more complex in mixed cropping systems where the legume and nonlegume are growing concurrently. Legumes usually take up less soil nitrogen in competition with nonlegumes and a greater fraction of the nitrogen they accumulate in a mixed crop is from fixed nitrogen. Somewhat surprisingly, the nitrogen fixation of intercropped beans (*Phaseolus vulgaris*) per hectare is not significantly different from beans raised in monoculture (36). This is attributed to competition between the maize and the bean for light and nutrients beginning after the decline in nitrogen-fixing activity in the bean's root nodules. Not all legumes shut down nodule function as early in the growth cycle as *Phaseolus vulgaris* but the effect of intercropping on nitrogen fixation may be detrimental in other intercropping systems.

It is a common misconception that there is substantial direct transfer of nitrogen from the legume to a nonlegume companion species in a mixed cropping system. There is no convincing evidence that actively growing, healthy legumes, whether grain or forage, excrete significant amounts of nitrogen from their roots or nodules. The hypothesis originally proposed by Virtanen and coworkers (73,74,75) that surface excretion of simple amino compounds from healthy, functioning legume root-nodules resulted in direct transfer of significant quantities of nitrogen to nonlegume companion species has found little support from other workers (45,7,47,80,81).

Subsequent research under carefully controlled conditions using the "fox box" technique (18) indicated that excretion of a wide range of substances from plant roots does occur, but that the quantities involved are small, less than 0.5 percent of the plant's nitrogen (65). Stated differently, a crop fixing 100 kg of nitrogen a year would excrete only 0.5 kg to the soil.

Nitrogen benefit to nonleguminous crops through association with companion legume species is considered to be of an indirect nature through loss and decay of shoot, root, and nodule tissue, or by recycling via the grazing animal, rather than by a direct pathway (76,15, 29,79).

Clearly then, mixed cropping systems that aim to use legume-fixed nitrogen for the benefit of a companion nonlegume species must match species so that the nonlegume is longer-lived than the legume. Nitrogen will be released in significant amounts only after cessation of active growth and decomposition of tissues of the legume. The maize/bean association used widely in Latin America shows this principal. Beans fix about 20 to 40 kg of nitrogen per growing cycle (34). Assuming 70 percent removal of nitrogen as protein in the legume grain, this leaves only 6 to 12 kg in legume residues, of which 3 to 6 kg (assuming 50 percent mineralization) will be mineralized in time to benefit the maize. Some estimates place the mineralization that can benefit a companion species as low as 20 percent. Consistent with this, it is not uncommon for there to be no detectable nitrogen benefit in companion crops that are intercropped with legumes.

It is evident that the BNF benefit to nonlegumes due to inclusion of legumes in a cropping system is small compared to the level of nitrogenous fertilizer used in the more intensive cereal production systems of the developed world. Thus, the principal contribution of BNF to human nutrition will continue to be via the protein in legume grains. Any suggestion of substantial replacement of nitrogen fertilization of cereals and root crops by biologically fixed nitrogen is unrealistic because these crops respond to levels of nitrogen fertilizer far greater than those currently supplied through BNF by legumes. Thus, there is an urgent need to devise ways to increase the contribution that BNF by legumes can make to cropping systems as a complement to nitrogen fertilizer-based production, rather than as an alternative to it.

Legumes can be managed to increase their nitrogen contribution. They vary in total nitrogen fixed, the proportion retained in non-harvested residues, the percentage nitrogen level in residual tissue, and the facility with which the organic nitrogen is mineralized. Thus, some species, managed in particular ways, will give greater residual nitrogen benefits. Given this, the priority now given in legume breeding programs to improving their harvest index, i.e., maximizing the fraction of each plant's total production that is removed as grain, should be called into question.

In summary, the principal benefits from BNF through the use of legumes in farming systems in the Tropics are derived from the dietary protein of the legume grain, the multiple uses that legumes serve for the subsistence farmer, and the greater stability of yield and financial return of intercrops over monocrops. The indirect benefits from contribution of biologically fixed nitrogen to companion or following species are small but are significant in the context of input levels in subsistence farming.

Insufficient reliable data exist on the potential benefits from enhancing, through inoculant technology, the nitrogen fixation in tropical legumes. It is tempting to recommend rhizobial inoculation of all legume sowings as an insurance measure against the risk of nodulation failures that would otherwise occur. However, inoculant technology does represent a cost, albeit small, and does add a degree of complexity to the sowing practice. Thus, inoculant technology should only be advocated when there is a known need to inoculate and a demonstrable benefit. Additionally, the concept and practice of inoculant technology is so foreign to the farmer's normal practices that it should not be recommended lightly. A subsistence farmer can be forgiven for not comprehending nor accepting a technology that involves sticking black powder containing bacteria to his seeds. This contradicts concepts which he had only recently learned, namely, that bacteria are bad and clean seed is important. It is to be questioned whether inoculant technology in this form will ever be accepted widely among subsistence farmers in the Tropics and Subtropics.

Unfortunately, many trials performed to evaluate inoculant technology with tropical legumes under tropical conditions have been done with imported inoculants that may not have contained acceptable levels of viable rhizobia. Lack of response to inoculation in such trials does not preclude the possibility that the legume could potentially benefit from inoculation. More recently, coordinated networks of trials have been initiated to determine whether there is an economic yield benefit from inoculation of legumes or not. INTSOY conducts international Soybean Rhizobium Inoculation Experiments (ISRIE) throughout the Tropics. CIAT distributes an International Bean Inoculation Trial (IBIT) throughout Latin America. The University of Hawaii coordinates an International Network of Legume Inoculation Trials (INLIT) offered for 13 agriculturally important legumes and involving a three-stage experimental program where cooperators throughout the Tropics select strains specifically for their legume variety and local soil conditions, thereby maximizing the opportunity for a yield response following inoculation.

FUTURE POTENTIAL OF LEGUME-BASED BNF TECHNOLOGY

Despite their seeming attractiveness for sustained productivity from low-input production systems, and despite also their consistent strategic use in many farming systems of the Tropics, legumes have remained minor crops in the systems where they occur (52). Why is this the case, and what factors would lead to greater use of nitrogen fixed biologically by legumes? A small-scale, subsistence farmer elects to raise those crops that best meet his household's needs but he also chooses one crop, at least, to sell or exchange for goods or services. Large-scale farmers consider the economic return and ease of management associated with the

crops they plant. A grower preference for cereals over legumes, when the grain is to be marketed, would be understandable. It is usual for yields of cereal grains to be as much as four times higher than legumes (typically 3.0 t/ha vs. 0.7 t/ha). Although the protein content is much higher in legumes (30 percent) than in cereals (6 percent), the market value of legume grains, albeit higher than for cereals, does not compensate the grower for their low relative yield.

Many factors will contribute to an increase in the use of legumes. Cereals will continue to be the major source of protein and calories for human nutrition worldwide, but an increase in importance of root and tuber crops and plantains over the next two or three decades is anticipated (58). Legumes can be expected to be one means of complementing the dietary quality of these starchy protein-deficient foods.

Another factor that has already caused a reappraisal of biological nitrogen fixation through legumes is the cost and availability of energy to produce nitrogen fertilizers. Already, 20 percent of nitrogen fertilizer production in the United States is cost-ineffective because of the cost of energy (in the form of natural gas) for the process. Producer costs have been calculated as $160/ton (61) whereas the selling price is in the range of $85 to $105/ton. Thus, biological nitrogen fixation through the use of legumes may be resorted to increasingly, not only to reduce the cost of on-farm inputs, but also to save foreign exchange and avoid overdependence on foreign powers.

But economic pressure alone will not guarantee adoption of BNF-based technology without compelling demonstration of greater benefits from BNF by legumes. The dramatic increase in interest in BNF since the energy crises of 1973, 1974, and 1979 has brought it under the scrutiny of agencies and individuals whose concern is its viability as a productive agricultural technology now rather than its often acclaimed potentials for the future.

The agricultural research community needs to undertake a comprehensive program of technology development where the relative distribution of funding and manpower investment is realistically prioritized. Research to stabilize grain legume yields can increase the contribution of biological nitrogen fixation in tropical farming systems more than much of the research on the BNF process per se in grain legumes. Similarly, research to select forage legume germplasm that is adapted to the soils and climates of the world's underused savannahs, and development of appropriate legume-based pasture management technology, can be expected to increase the use of biological nitrogen fixation even without further research on the BNF process. These statements assume that effective nodulation can be guaranteed. Since this is not always the case, those specific aspects of BNF research that study the factors that limit nodulation and nitrogen fixation in tropical soils should be given highest priority.

CONSTRAINTS ON IMPLEMENTATION OF BNF TECHNOLOGY

There are still many unknowns in the scientific understanding of BNF, and research into the biochemistry and genetics of the process is particularly intense and competitive. But few, if any, of these unknowns are really constraining the implementation of legume-based BNF technology. The basic principles of inoculant technology have been known for many years and have already made major contributions to agricultural production—initially in Australia and, more recently, worldwide as soybean cultivation has been increasing. The real constraints to fuller implementation of BNF technology relate to delivery of the tech-

nology, both to potential inoculant producers and to farmers, and acceptability of the technology.

There has not been adequate demonstration, under realistic conditions in the developing countries, of the yield increases and/or reduced fertilizer needs that are repeatedly stated to be the benefits of BNF technology. In some cases, inoculation trials have been performed and no response obtained. But these trials have been mainly with imported inoculants, the quality of which at the time of their use was not or could not be verified. Thus, a related constraint is the lack of trained personnel with the essential combination of agronomic and microbiological skills for executing production-oriented research on BNF technology.

Research is necessary to adapt BNF technology and develop appropriate *Rhizobium* strains and inoculation procedures for use in the Tropics and Subtropics. Current inoculation technology as used in the United States and Australia is suited to legumes grown under favorable conditions with relatively high complementary agronomic inputs. Transferability of this technology to situations where the legumes are grown under marginal conditions with minimal inputs, and confronted with one or more soil and climatic stresses, is in some doubt (37).

It is the genotype of the legume that is to be inoculated that is the prime determinant of the strain used in rhizobial inoculants, rather than the characteristics of the soil where the inoculant will be introduced. This is contrary to what is expected by many first-time users.

For example, in providing inoculant services in Latin America and Hawaii, it has been common to receive data from soil analysis together with requests for inoculants. Farmers expect the selection of legume inoculant to be made after consideration of local soil and climate, just as would be the choice of crop variety. Yet there are few instances in which an inoculant strain is recommended in commercial production because of the soil characteristics. *Rhizobium* strain CB 81 is recommended for *Leucaena leucocephala* sown in acid soil and NGR 8 for alkaline soils (48).

When soil characteristics are very different, the response to inoculation and the relative performance of rhizobial strains is also different. Even apparently similar soils can show different performances. Thus some authors advocate that simple "need-to-inoculate" trials always be performed at the local level due to the unpredictability of the response to inoculation (11,22,23). This suggestion would result in legume inoculation being tested, essentially by trial-and-error, at every site where legumes are to be grown. Inoculation technology needs to be more transferable than this, otherwise its value as an agrotechnology is questionable.

There a ɜ significant differences between sites in the size of their indigenous rhizobial populations (42,55) and in the range of strains of *Rhizobium* in the indigenous microflora (43,55). Such differences have been attributed to the effect of soil factors (43,5) though the possibility of widespread correlations between specific soil characteristics and rhizobial occurrence in tropical soils has not been critically examined.

The response by tropical legumes to inoculation with rhizobia also varies from site to site (11,22,34,35,44,16). Such variation has been attributed to: differences in number, effectiveness, and competitiveness of native strains (40, 27,55,38); variation in quality of the inoculant at its time of use (14); and variation in soil nitrate levels (57). The possibility that the response to inoculation could be predicted on the basis of a more thorough description of soil and environmental characteristics has not been tested.

The relative performance of strains selected under optimal conditions for a specific legume is variable, depending on the site where they are introduced (16). With inoculants that contain a mixture of strains of *Rhizobium*, it is common for one strain to dominate in the resulting nodule population (33,39). The possibility that rhizobial strains might be selected for adaptation to particular soil and environ-

mental conditions is not now exploited in tropical agriculture.

A serious constraint to fuller implementation of BNF technology is the lack of domestically produced, high-quality inoculants in the Tropics and Subtropics. Thus, factors which deter government organizations or private enterprise from undertaking inoculant production in a particular country are also constraining BNF technology. Among these are: high capital cost of inoculant production plant (of the type used in the United States and mistakenly assumed to be needed in any production plant); high operational cost associated with retaining a professional and well-trained staff to run the plant; operational risks associated with losses due to such factors as contamination; absence in most developing countries of an adequate infrastructure that would permit marketing and distributing a biological product with notorious vulnerability to high temperatures; reticence to embark on an enterprise in advance of official control standards being established (compounded by official reticence to set standards until there is an industry to be controlled); and insufficient demand and uncertain future demand for inoculants.

The present nature of BNF technology meets considerable farmer resistence, i.e., the coating of seeds with peat inoculant. In Brazil, packets of inoculant are included "free" by some seed distributors with all seed sales. However, the inoculant is frequently discarded by farmers not only because of the nuisance associated with its use, but also in part because of an unfortunate impression that if inoculant is "free" it is of little value.

The cost of inoculants is not usually a constraint to farmers who outlay capital for seed. Inoculant will seldom exceed 1 percent of the seed cost. For subsistence farmers who do not ordinarily purchase seed, the capital outlay for inoculant, albeit small, may be a disincentive. Cost becomes a more important consideration with granular forms of inoculant because the rate of application is much greater than with seed-applied inoculant.

BNF technology is a difficult technology to deliver by normal extension mechanisms. Thus, a lack of illustrative pamphlets and other aids both for extension agents and the farmers is also a constraint on implementation of BNF technology at the farm level.

Furthermore, few of the senior administrators and decisionmakers who determine agricultural policy in the developing countries are fully aware of the applications for legume-based BNF technology. Most policymakers are aware of some of the attributes of legumes. Relatively few appreciate the role played by biological nitrogen fixation, and among those an even smaller number recognizes that it may be essential to employ specific technologies to ensure that maximum nitrogen fixation occurs. Thus, there is a need for educational material, specifically developed for decisionmakers, bringing to their attention the need to adapt available technology to the particular circumstances where it is to be employed.

As BNF technology is being implemented, new constraints are emerging that are best described as "scientific" and are researchable. For example, some countries do not have peat deposits suitable for carrier materials for inoculant production and alternate materials must be identified and validated. Also, specific soil and climatological stresses such as extreme soil acidity and the associated high levels of toxic elements like aluminum and manganese may require selection of strains of rhizobia tolerant to those conditions.

The large number of competent researchers who expend their energies and resources researching aspects of BNF other than limiting factors such as the examples cited above is also a constraint on fuller implementation of BNF technology. Funding agencies do not always recognize a distinction between applied and less practical research in the area of biological nitrogen fixation. Biological nitrogen fixation has great pertinence to agriculture production in developing countries, but not all research conducted under the BNF umbrella is applicable in agriculture.

SCENARIO FOR FULL IMPLEMENTATION ON BNF TECHNOLOGY

The constraints on fuller implementation of BNF technology are not solely scientific, but include cultural, socio-economic, and political factors. Thus, the scenario where BNF might realize its potential would necessarily be multifaceted and comprehensive.

The current trend toward energy-efficient farming systems to reduce capital outlay for imported fertilizers can be expected to continue and intensify. Manufacture of nitrogen fertilizers requires high energy consumption, so their price and availability is influenced increasingly by oil-rich nations. There is added attractiveness in alternate nitrogen sources to avoid further dependence on foreign powers. Legume-based BNF technology is the major option available and is likely to be resorted to more and more.

The use of legumes and appropriate inoculant technology has the potential to increase the amount of biologically fixed nitrogen entering agricultural production systems. Given that the main value of legumes is their high-protein grain, rather than their nitrogen contribution to nonleguminous food crops such as cereals and root crops, the scenario for full realization of BNF technology's potential would need to include a swing in consumer preferences away from crops that depend so heavily on nitrogen fertilizer. Thus, in the gambit of BNF research priorities, attention will need to be given to learning the cultural and scientific bases for these preferences and to alleviating the constraints to greater consumer acceptance of legumes.

The major increases in benefits from legume-based BNF technology will arise through an increase in the total acreage in legume production; innovative use of legumes in roles they have not previously occupied; and by ensuring that biological nitrogen fixation in legumes is maximum through appropriate inoculation technology. Much remains to be done to improve the role now played by biological nitrogen fixation components. There is a wide discrepancy between farmers' yields and the known yield potential of grain legumes. Furthermore, it is disconcerting that in the majority of legume trials that include nitrogen fertilizer application, the legumes responded to nitrogen fertilization. This is disconcerting because it means that even when legumes were grown under favorable management in experiments, let alone in farmers' fields, the symbiotic association of the legume with rhizobium was defective. Therefore, the potential to double or triple the nitrogen benefits described in this report exists through development of technology that would assure establishment of maximally effective rhizobial symbioses in tropical legumes under tropical conditions.

Greatest future potential would appear to rest in developing:

- legume-based pastures and viable multiple-cropping systems including legumes for underused savannahs;
- agroforestry systems that combine fast-growing, nitrogen-fixing trees, legumes, and other crops to meet the food and fuel requirements of the rural poor;
- fast-growing leguminous trees for reforesting water catchment areas following forest clearance;
- legume-based cropping systems to give sustained productivity in tropical soils following jungle clearance; and
- selection of deep-rooted, drought-tolerant leguminous trees that can serve as browse species in the world's dry lands.

Reference has already been made to the need to exploit fully the variation in host plant, rhizobial strain, and environment interaction when selecting the optimal BNF package for each circumstance. Legume programs should retain the services of a professional microbiologist, but this suggestion is not practical. First, few legume programs can afford the luxury of a full-time microbiology position and second, there is a worldwide shortage of professional soil microbiologists that is unlikely to be alleviated significantly for about 10 years. The world's major multidisciplinary legume pro-

grams should, however, have their own microbiologists. This is already the case with the IARC programs for beans, cowpeas, pigeon peas, groundnuts, chickpea, and tropical forages. INTSOY, working with soybean, has its own soil microbiologist. Also, there are several national legume programs where microbiological support is integrated through a participating institute with expertise in the BNF area (e.g., Brazil, India).

The needs of the other legume programs for BNF expertise could be met through the provision of one (or more) BNF Resource Center(s). Such centers could provide technical assistance, offer support services (germplasm and information), provide professional and technical training, and conduct research necessary to adapt BNF technology to specific local conditions when it is beyond the capability of local researchers. Such centers would require a critical mass of BNF researchers to be able to carry out a comprehensive support program and still retain a capability to respond to technical assistance requests.

The BNF Resource Center(s) would best be located at universities in developed countries, and preferably in the Tropics. A university site would help provide professional training, important if national institutions in developing countries are to be able to sustain their own BNF programs. Short-term, non-degree training programs in BNF technology should be offered to key personnel working on research programs involving the legume/rhizobium symbiosis. This is more effective in the short term than Ph.D. or M.S. programs which tend to be a passport out of research into better paid administrative positions for many graduates returning to their home country. The short courses should be offered in cooperation with developing country institutes to generate a regional capability for offering such courses. They should be complemented by on-the-job training tailored to the needs of selected individuals that would be conducted at the BNF Resource Center and include visits to pertinent industry facilities.

Such BNF Resource Centers would engage information specialists to develop communications materials suitable for the many clientele groups. This would range from newsletters for administrators to pamphlets for extension agents and include providing information for developing country researchers, who often do not have access to libraries.

Agricultural research tends to focus manpower and resources on improvement of single commodities. Some organizations, like IARCs, are characterized by multidisciplinary teams with specific crop and/or geographic mandates. Establishing a BNF Resource Center would be considered by some as a return to discipline-oriented research. This author contends that the key element in the success of commodity programs such as some of those in the IARCs has been that they are *highly focused* and *actively managed* in pursuit of *well-defined research priorities* rather than attributable to the commodity approach per se. A program investing manpower and financial resources in an actively managed BNF program that is sharply focused on the constraints to full implementation can be expected to make real progress. The specialized and sophisticated nature of rhizobium bacteriological expertise and the scarcity of experienced manpower is further justification for assembling a critical mass of rhizobiologists in a single BNF Resource Center.

An additional advantage in the existence of such a BNF Resource Center would be a capability to extend BNF technology developed at a particular place to other crops and regions. Staff of the BNF Resource Centers would travel as required and undertake short (1 to 3 months) or longer (3 months to 3 years) assignments in support of specific outreach activities when warranted. Only travel would help the personnel of the BNF Resource Centers focus their attention on researchable constraints in real agricultural situations in the developing countries. Additionally, the Resource Centers would work closely with other universities and research organizations where specific research

on factors limiting BNF use could be referred under subcontract.

The BNF Resource Center would need to develop links with commercial inoculant producers to begin appropriate assistance programs for government organizations or private enterprise in developing countries contemplating inoculant production. Such programs would cover not only technical aspects of the production of inoculants but also the business aspects of small enterprise production, marketing, and distribution of inoculants. The BNF Resource Center should develop specifications, including sources of all equipment items, for inoculant production facilities that would be feasible at levels of capital investment ranging from $50,000 to as high as $1 million. The Center should also advise governments on an appropriate mechanism for quality control.

The Center would also need to develop strong links with major legume germplasm centers and those involved in legume improvement to encourage simultaneous exploitation of host legume and rhizobial germplasm in selections for particular soils and climates.

The BNF Resource Center would take a major organizational responsibility for calling workshops and scientific meetings to coordinate international experimentation and disseminate results.

The major activity to be undertaken by the BNF Resource Center would be the coordination of competent, standardized experiments designed to generate the data necessary to quantify the economic yield benefit attributable to legume inoculation under field conditions. Such trials would also serve as local demonstrations of the benefits from legume inoculation.

The core budget for such a BNF Resource Center should be guaranteed by the host government through its agency responsible for international development. The host institution (university) cannot realistically be expected to provide direct financial support for such a Center given that the Center staff will not have conventional instructional responsibility and that the research will aid mainly foreign nations with only minor benefits for agriculture where the Center is located. The mandate of a BNF Resource Center is international and therefore, the support should be international.

There is understandable reticence on the part of international funding agencies to expend resources in a center located in a developed country. The author contends that it is in the best interests of the developing countries that BNF programs be conducted by a Center located in the Tropics but sited in a developed country where it can receive unimpeded logistic support for its sophisticated operations and enjoy continuity of service from high calibre professional staff. Such a Center would be ultimately more cost effective than fragmented support to a myriad of in-country programs, an approach that often causes wasteful duplication of effort. Furthermore, support of a BNF Resource Center, for example in the United States with funding by USAID, would be prudent use of public funds. A large share of the budget would be expended in the United States sustaining employment of U.S. residents and strengthening a U.S. institution without lessening the support for the developing countries. Additionally, a greater degree of control could be exercised over the activities of a U.S.-based Center than is possible with grants to foreign institutions.

Agencies that could be anticipated to contribute to a BNF Resource Center would be: FAO, UNEP, UNESCO, and UNDP. Technical assistance on a continuing basis to any specific country ought to be funded externally as a special project with funding arranged by that country from its national budget and international development assistance grants or loans.

As a hypothetical estimate, the author suggests the following distribution of $10 million toward the implementation of legume-based BNF technology (table 1). It is assumed that the $10 million is additional to current support for BNF.

Table 1.—Allocating Funds for a BNF Resource Center (How to Spend $10 million on BNF)

Salaries (6 professional and 12 subprofessionals)	$3,000,000
African network of trials/demonstrations	200,000
American network of trials/demonstrations	200,000
Asian network of trials/demonstrations	200,000
Training programs in technology	500,000
Professional (M.S., Ph.D.) training	150,000
Information services	120,000
Germplasm services	100,000
Workshops/conferences (3 regional, 1 global)	270,000
Research	
Simplification of inoculant production	90,000
Innovative inoculation methods	90,000
Stress tolerance in inoculant strains	150,000
Quantifying N fixation/cycling in cropping systems in the tropics	220,000
Advisory services	200,000
Contingency fund	60,000
Indirect costs	1,350,000
BNF Resource Center sub-total	$7,000,000[a]
Pilot Inoculant Plants	
Zambia (year one)	250,000
Ivory Coast (year one)	100,000
Others (beginning third year)	1,000,000
Nitrogen-Fixing Tree Research (initially in Haiti/Thailand/Senegal)	500,000
Socio-economic Evaluation of BNF Technology	250,000
Outreach Programs of BNF Resource Center (beginning year 3)	
Zambia	300,000
Bangkok	300,000
Peru	300,000
GRAND TOTAL	$10,000,000

[a]This figure is low for the level of operations envisioned and is possible because a center with appropriate equipment and buildings has already been established and is operating in the proposed BNF Resource Center mode (i.e., University of Hawaii NifTAL Project).

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Acronyms

ARC —Agricultural Research Center
BNF —Biological Nitrogen Fixation
BTI —Boyce Thompson Institute (Cornell University)
CB 81 —CSIRO, Brisbane, Rhizobium strain 81
CGIAR —Consultative Group on International Agricultural Research
CIAT —Centro Internacional de Agricultural Tropical (Colombia)
CRSP —Cooperative Research Support Program
FAO —Food and Agriculture Organization (of the United Nations)
IARC(s) —International Agricultural Research Center(s)
IBIT —International Bean Inoculation Trial
IBPGR —International Board for Plant Genetic Resources
ICARDA —International Center for Agricultural Research in Dry Areas (Syria)
ICRISAT —International Crops Research Institute for the Semi-Arid Tropics (India)
IITA —International Institute for Tropical Agriculture (Nigeria)
INLIT —International Network of Legume Inoculation Trials
INTSOY —International Soybean Program (University of Illinois)
ISRIE —International Soybean Rhizobium Inoculation Experiment
MIRCEN —Microbiological Resources Center (UNEP/UNESCO project)
NGR 8 —New Guinea, Rhizobium strain 8
NifTAL —Nitrogen Fixation by Tropical Agricultural Legumes (University of Hawaii)
OTA —Office of Technology Assessment (U.S. Congress)
SEA/CR —Science and Education Administration/Cooperative Research (USDA)
UNDP —United Nations Development Program
UNEP —United Nations Environmental Program
UNESCO —United Nations Educational, Scientific, and Cultural Organization
USAID —United States Agency for International Development
USDA —United States Department of Agriculture

Chapter X

Mycorrhiza Agriculture Technologies

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Contents

	Page
Introduction—What Are Mycorrhizal Fungi?	185
Ectomycorrhizae	185
Vesicular-Arbuscular (VA) Mycorrhizae	185
How Do Mycorrhizal Fungi Improve the Growth of Agricultural Plants?	187
Mycorrhizae as Substitutes for Fertilizers	189
Current Commercial Use of Mycorrhizal Fungi	191
Disturbed Sites	191
Fumigated or Chemically Treated Sites	191
Greenhouses	192
Commercial Production and Inoculation With Mycorrhizal Fungi	192
Potential Uses of Mycorrhizal Fungi	195
Constraints on the Commercial Use of Mycorrhizal Fungi	197
Effects of Mycorrhizal Fungi on Agriculture	198
Conclusions and Recommendations	198
References	199

Table

Table No.	*Page*
1. Estimated Cost of Production of Vesicular-Arbuscular Mycorrhizal Inoculum on Sudangrass in 4 Inch Pots	194

Figures

Figure No.	*Page*
1. Diagram of a Typical Ectomycorrhiza Including the Hartig Net, Fungal Mantle, and External Hyphae	185
2. Diagram of a Typical Vesicular-Arbuscular Mycorrhiza Including Vesicles, Arbuscules, Spores, and External Hyphae	186
3. The Growth of Citrus Seedlings With and Without VA Mycorrhizal Fungi and at Different Nutrient Levels	188
4. Dry Weights of Mycorrhizal and Non-Mycorrhizal Brazilian Sour Orange and Troyer Citrange Seedlings Fertilized With Different Amounts of Phosphorus	190
5. Proposed Scheme for the Commercial Production of Vesicular-Arbuscular Mycorrhizal Inoculum	193

Chapter X

Mycorrhiza Agriculture Technologies

INTRODUCTION—WHAT ARE MYCORRHIZAL FUNGI?

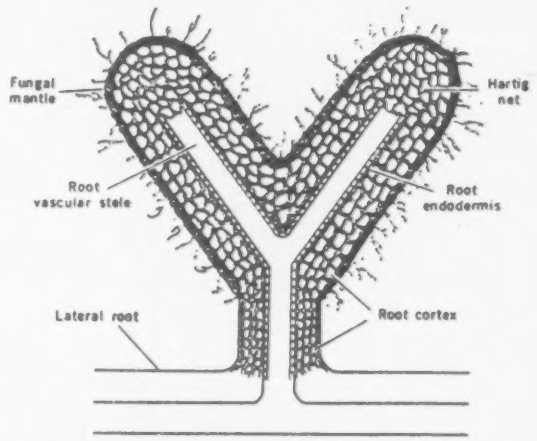
Mycorrhizal fungi are beneficial fungi that are associated with plant roots via a symbiotic association whereby both the host plant and the fungus benefit. Mycorrhizae are the structures formed by the symbiotic association between plant roots and mycorrhizal fungi. Mycorrhizae contain both plant roots and fungal tissues. In nature, mycorrhizae are far more common than non-mycorrhizal roots (24,92,94). Nearly all plant species are associated with mycorrhizal symbionts. Because of their importance to plants and their widespread distribution, mycorrhizae must be considered in all aspects of plant ecology, crop science, and agriculture.

Mycorrhizal fungi are divided into four very different types (66): ectomycorrhiza, vesicular-arbuscular mycorrhiza (abbreviated as VA mycorrhiza), ericaceous mycorrhiza, and orchidaceous mycorrhiza. As indicated by their names, ericaceous mycorrhiza and orchidaceous mycorrhiza are associated with ericaceous plants (blueberries, cranberries, azaleas, etc.) and orchidaceous plants (orchids), respectively. Because of the relatively low economic impact of these plants and the small amount of available data on these types of mycorrhiza, they will not be discussed further.

Ectomycorrhizae

Ectomycorrhizae are associated primarily with trees such as pine, hemlock, spruce, fir, oak, birch, beech, eucalyptus, willow, and poplar. Ectomycorrhizae are formed by hundreds of different fungal species belonging to the Basidiomycetes (mushrooms and puffballs) and Ascomycetes (cup fungi and truffles). These fungal symbionts are stimulated by root exudates and grow over the surface of host feeder roots to form a thick fungal layer known as a fungal mantle (figure 1). Hyphae of ectomycorrhizal fungi penetrate between the cells of the host root, develop around the root cortical cells, replace the host middle lamella, and form what is called the "Hartig net"—the distinguishing feature of ectomycorrhizae. In response to the fungal invasion, the host roots usually swell substantially and may branch dichotomously or in a coralloid manner. The root cells are not injured, however, and function of the roots is enhanced, as we shall discuss.

Figure 1.—Diagram of a Typical Ectomycorrhiza Including the Hartig Net, Fungal Mantle, and External Hyphae (courtesy D. H. Marx)



Vesicular-Arbuscular (VA) Mycorrhizae

VA mycorrhizal fungi have the widest host range and form by far the most common type of mycorrhizae. VA mycorrhizae occur on liverworts, mosses, ferns, some conifers, and most broad-leaved plants. Only 14 families that are considered primarily non-mycorrhizal (28). The important crop families that are non-mycorrhizal are Cruciferae (cabbage, broccoli, mustard, etc.); Chenopodiaceae (spinach, beet,

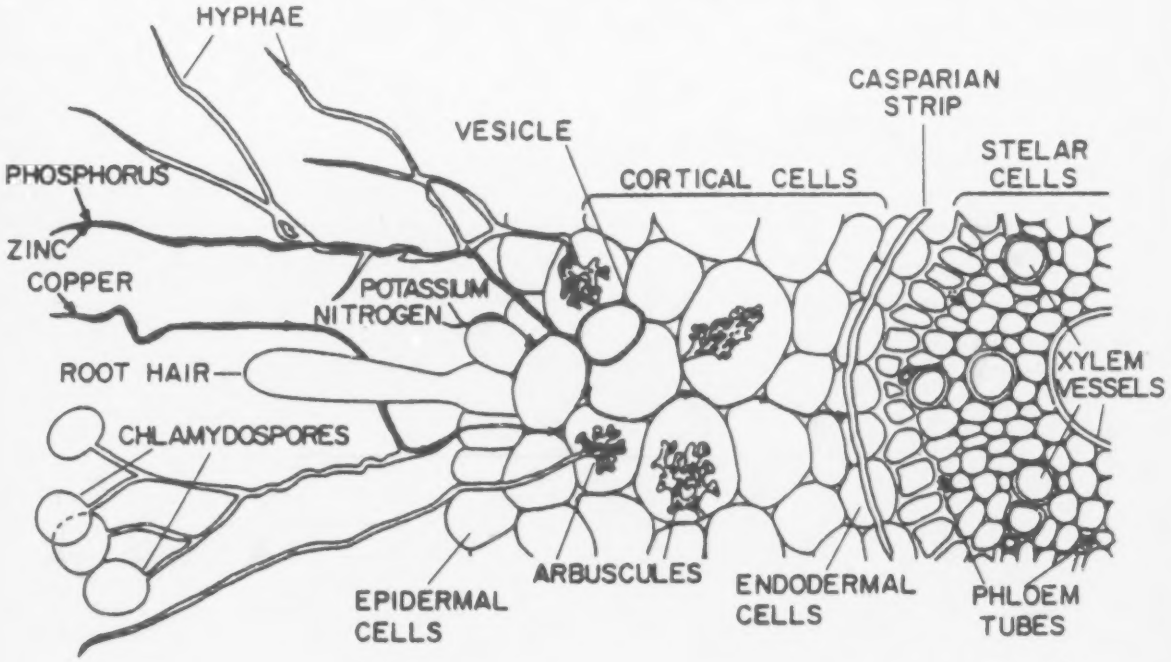
etc.); Cyperaceae (sedges); and Caryophyllaceae (carnation, pinks, etc.). Wetland rice also is usually non-mycorrhizal. Nearly all other important agronomic crops including wheat, potatoes, beans, corn, alfalfa, grapes, date palms, sugar cane, cassava, and dryland rice are associated with VA mycorrhizal fungi. Although many trees have ectomycorrhizae, most have VA mycorrhizae. Sixty-three of sixty-six tropical trees in Nigeria (77) are associated with VA mycorrhizae. So are most important tree crops such as cocoa, coffee, rubber, and citrus. Some trees such as juniper, apple, and poplar can have either ectomycorrhizae or VA mycorrhizae.

The fungi that form VA mycorrhizae, about 80 species, are in a few genera in the Zygomycetes class of fungi. They are so common in soils that literally any field soil sample from arctic to tropical regions will contain these fungi (66).

The hyphae of VA mycorrhizal fungi penetrate directly into the root cortical cells of host plants. Inside of the host plant cells, VA mycorrhizal fungi form minute coralloid structures known as arbuscules (figure 2). Arbuscules are thought to be the site of nutrient transfer between the symbiotic partners. The host plants obtain fertilizer nutrients from the mycorrhizal fungus while the fungus obtains sugars or other food materials from the plant. Although the arbuscule of VA mycorrhizal fungi occurs inside root cells, they remain covered by the host cell membrane and so are not in direct contact with the host cytoplasm. Vesicles are balloon-like mycorrhizal fungus structures that usually form inside the host root. These structures are thought to be storage organs that the fungus produces to store nutrient materials inside of the plant host.

VA fungi also produce abundant spores either inside or outside of host roots. These

Figure 2.—Diagram of a Typical Vesicular-Arbuscular Mycorrhiza Including Vesicles, Arbuscules, Spores, and External Hyphae



spores are the survival structures of VA mycorrhizal fungi. They are long-lived and extremely resistant to most unfavorable soil conditions. These spores are responsible for the widespread occurrence of VA mycorrhizal fungi in nearly all soils throughout the world. Despite the intracellular penetration by VA mycorrhizal fungi, they do not affect the roots' outward appearance except by inducing a yellow coloration in some hosts (4). Detection of VA mycorrhizal roots is best done by staining roots and examining them microscopically for the presence of hyphae, arbuscules, or vesicles (73).

Arbuscules of VA mycorrhizal fungi are short-lived and generally survive for less than 2 weeks before they are digested by the host plant (61,90). Plant roots normally release large quantities of chemical "exudates" into the root zone (8). Since the arbuscules are covered by the host membrane it is thought that the symbiotic association is regulated by the host plant via the cell membrane. The more nutrient materials released by the plant membrane to the arbuscule of the mycorrhizal fungus, the more abundant the mycorrhizal colonization (76). By restricting nutrients passing through the plant membrane the plant is capable of restricting mycorrhizal infection in roots. A similar mechanism can be postulated for the regulation of ectomycorrhizae by plant roots.

HOW DO MYCORRHIZAL FUNGI IMPROVE GROWTH OF AGRICULTURAL PLANTS?

The VA mychorrhizal symbiosis results in marked increase in crop growth and development. For example, inoculation of fumigated sand or soil with VA mycorrhizal fungi will increase the growth of citrus by as much as 1600 percent (figure 3); (42), grapes by 4,900 percent (74), soybeans by 122 percent (84), pine by 323 percent (100), and peaches by 80 percent (44). Growth responses due to VA mycorrhizal fungi have been observed in cotton (82), tomatoes (16), corn (27), wheat (41), clover (75), barley (5), potatoes (7), ornamental plants (99), and in many other crops.

VA mycorrhizal fungi stimulate plant absorption of phosphorus (85,74,28,62), zinc (44,61), calcium (84), copper (84,85,60,42), iron (60), magnesium (36,61), and manganese (84,61). Increased uptake of phosphorus is perhaps the most important benefit provided by mycorrhizal fungi.

Most researchers agree that the increase in effective nutrient absorbing surface provided by mycorrhizal fungi is primarily responsible for the increase in uptake of soil nutrients by mycorrhizal plants. Hyphae from figure 3 mycorrhizal plant roots can extend up to 8 cm into the surrounding soil and transport nutrients this distance back to the roots (83).

VA mycorrhizal fungi may increase the effective absorbing surface of a host root by as much as 10 times (6). Nutrient ions such as phosphorus, zinc, and copper do not diffuse readily through soil. Because of this poor diffusion, roots deplete these immobile soil nutrients from a zone immediately surrounding the root. Mycorrhizal hyphae extend into the soil past the zone of nutrient depletion and can increase the effectiveness of absorption of immobile elements by as much as 60 times (6). Others have calculated that approximately 50 cm of mycorrhizal hyphae per cm root is necessary to account for the uptake of phosphorus by mycorrhizal plants (89). Experimental observations indicate that plant roots can have more than 80 cm of mycorrhizal hyphae, more than the amount necessary to account for the observed phosphorus uptake.

Plant uptake of mobile soil nutrients such as nitrogen and potassium is rarely improved by mycorrhizal fungi. Normal soil diffusion is adequate to supply roots of plants with these nutrients whether the roots have a large absorbing surface or not. Generally, plants that are most dependent on mycorrhizal fungi for nutrient uptake are those having roots with a low surface to volume ratio; that is, plants with coarse, fleshy roots with few root hairs (2).

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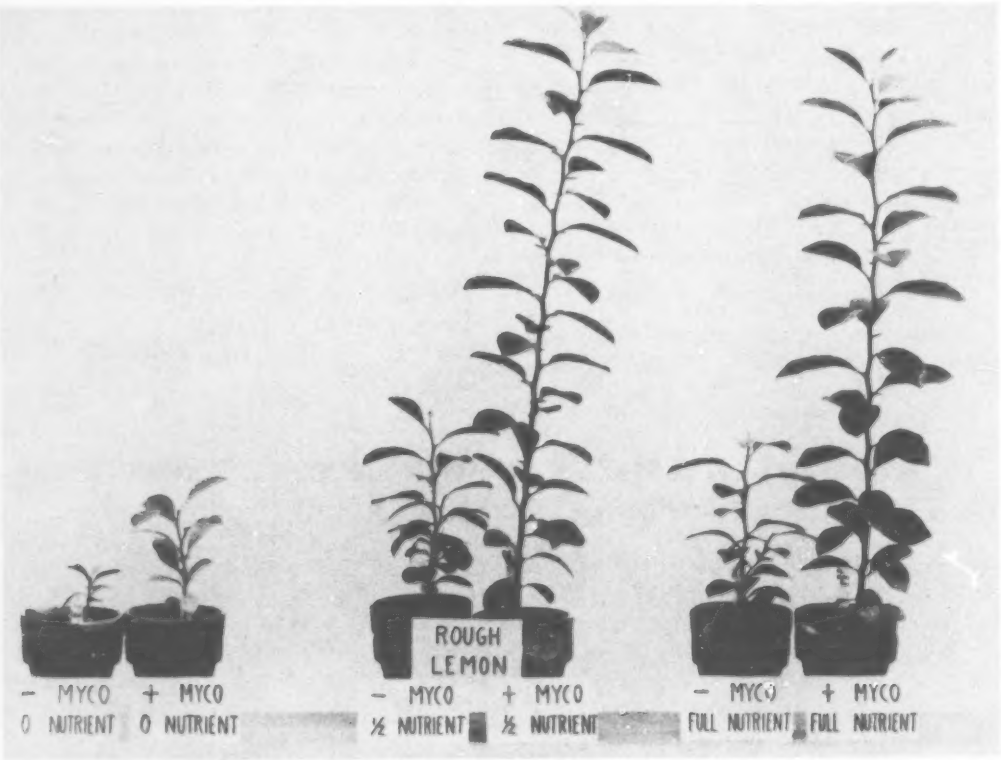
Figure 3.—The Growth of Citrus (Rough lemon) Seedlings With (+Myco) and Without (−Myco) VA Mycorrhizal Fungi and at Different Nutrient Levels



Although some scientists speculate that mycorrhizal fungi can solubilize and absorb nutrients that are unavailable to plant roots, there is little evidence to support this claim. Sanders and Tinker (88) showed conclusively with ^{32}p-labelled phosphate that mycorrhizal fungi use the same phosphorus sources as do plant roots but they are able to absorb from a larger soil volume and so are responsible for the vast majority of phosphorus absorption by crop plants.

Mycorrhizal fungi can also enhance water transport in plants (87) and prevent water stress under some conditions (54). This probably is not a direct effect of mycorrhizal fungi, but instead is because of the improved nutrient status provided by the mycorrhizal fungi. Mycorrhizal fungi can endure much dryer soil conditions than can most plants and it is thought that plants may benefit from mycorrhizal infection under drought or water-stressed conditions (66,86). Ectomycorrhizae, in particular, with their mantle surrounding the roots, may provide a physical barrier against root dessication.

Considerable evidence exists to suggest that mycorrhizal plants may be better equipped to withstand the toxic effects of salt. Calcium, magnesium, and sodium concentrations in non-mycorrhizal citrus were 41 percent, 36 percent, and 150 percent greater than in mycorrhizal citrus (55). Hirrel and Gerdemann (35) found that mycorrhizal fungus increased bell peppers tolerance to salinity. Trappe, et al. (98), indicated that VA mycorrhizal fungi provided resistance to the toxic effects of arsenic. Mycorrhizae may also provide tolerance to excessive soil manganese and aluminum (34).

Mycorrhizal fungi also act to increase nodulation by symbiotic nitrogen-fixing bacteria

such as *Rhizobium* (64,69). Mycorrhizal fungi may stimulate other beneficial rhizosphere organisms as well (1).

Ectomycorrhizal fungi have been reported to provide resistance to plant disease in many plants (48). Although mycorrhizae never confer complete immunity, they often appear to reduce the severity of disease or symptom expression. Resistance of ectomycorrhizae to disease may result from (48):

- mechanical protection by the mantle,
- better plant nutrition,
- production of antibiotics by the mycorrhizal fungus,
- competition for infection sites,
- formation of phytoalexins, and
- alteration of root exudates.

Evidence is accumulating that VA mycorrhizal fungi exert similar effects on plant pathogens. Schenck, et al. (91), has reported mycorrhizal resistance to root-knot nematodes. Schonbeck (93) has examined a variety of foliar and root pathogens on mycorrhizal plants and concluded that root pathogens (*Thielaviopsis, Fusarium,* nematodes, etc.) are usually inhibited by mycorrhizal fungi while foliar pathogens (viruses, rusts, etc.) are often more severe on mycorrhizal plants. Davis, et al. (21,22), and Davis and Menge (20) concluded that the VA mycorrhizal fungus *Glomus fasciculatus* produced little resistance to Phytophthora root rot in citrus and indeed increased Phytophthora root rot in avocado and Verticillium wilt in cotton. VA mycorrhizal effects on disease may result from improved phosphorus nutrition because of the increased absorbing surface of the mycorrhizal hyphae. This effect is magnified when the roots' normal absorbing capacity is reduced because the roots are partially decayed.

There have been reports of mycorrhizal fungi actually reducing growth of some plants (11, 39,13). These parasitic effects are rare and the reason for them is not understood, but they apparently occur in grasses, cereals, and tomatoes at or above optimum soil nutrient levels when the plant is actively regulating mycorrhizal invasion.

MYCORRHIZAE AS SUBSTITUTES FOR FERTILIZERS

In the past 40 years the use of agricultural fertilizers has more than doubled. Crop yields have risen dramatically as a result. However, because of shortages in some fertilizer supplies and the high cost of energy, the cost of fertilizers has risen tremendously. Agricultural economists indicate that as energy costs rise the most responsive agricultural input is fertilizer. That is, as energy costs rise, fertilizer use will decrease. This response is a dangerous one since chemical fertilizers are said to account for one-third to one-half of the current U.S. agricultural output (47).

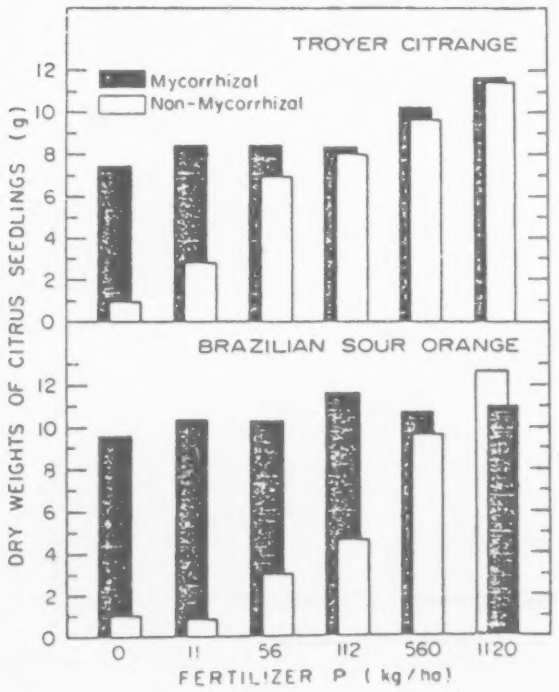
Estimates indicate that agriculture uses between 2.6 and 4.4 percent of all U.S. energy use. Fertilizers and their application comprise 30 to 45 percent of the total agricultural energy use. Nitrogen is the main energy user, with phosphorus and potassium accounting for only 16 percent of the fertilizer energy use (47).

Because mycorrhizal fungi increase the efficiency of fertilizer use, they can be thought of as "biotic fertilizers" and can indeed be substituted for substantial amounts of some fertilizers (53,55). Mosse (61) maintains that 75 percent of all phosphorus applied to crops is not used during the first year and reverts to forms unavailable to plants. In soils high in pH, aluminum, or calcium carbonate, nearly 100 percent of the phosphorus fertilizer can be immobilized to nonusable forms via chemical reactions in the soil. Tropical oxisols and ultisols are notorious for their capacity to immobilize phosphorus. Because mycorrhizal plants are better suited to exploiting soil with low amounts of available phosphorus, zinc, and copper, the

addition of large amounts of these fertilizers each year may be unnecessary. Menge, et al. (55), compared mycorrhizal citrus seedlings with non-mycorrhizal seedlings that received various amounts of phosphorus fertilizer (figure 4).

Mycorrhizal Troyer citrange that received no fertilizer phosphorus were equal in size to non-mycorrhizal Troyer citrange that received 112 kg phosphorus per hectare. Similarly, mycorrhizal Brazilian sour orange that received no fertilizer phosphorus were equal in size to non-mycorrhizal plants that received 560 kg phosphorus per hectare. Concentrations of phosphorus in non-mycorrhizal Brazilian sour orange leaf tissue were never above 0.05 percent (less than 0.9 percent phosphorus indicates phosphorus deficiency) even when seedlings were fertilized with 1,120 kg phosphorus per hectare. Concentrations of phosphorus in leaves of mycorrhizal Brazilian sour orange were above deficiency levels in all seedlings fertilized with more than 56 kg phosphorus per hectare. Concentration of phosphorus in leaves of mycorrhizal Troyer citrange were never in the deficiency range even when plants were not fertilized with phosphorus.

Figure 4.—Dry Weights of Mycorrhizal and Non-Mycorrhizal Brazilian Sour Orange and Troyer Citrange Seedlings Fertilized With Different Amounts of Phosphorus



Non-mycorrhizal Troyer citrange, on the other hand, required over 56 kg phosphorus per hectare before adequate phosphorus concentrations were restored to the leaves. At 1980 retail costs for triple super-phosphate, it appears that use of mycorrhizal fungi could result in savings of $111 to $558/ha ($45 to $226/acre) in the cost of phosphorus fertilization of citrus in fumigated nursery soil. In one California citrus nursery, it was found that inoculation with mycorrhizal fungi could reduce phosphorus fertilization by two-thirds and save $652/ha ($264/acre). Similar savings in phosphorus fertilizers have been shown by Kormanik, et al. (43), in fumigated forest nurseries in the production of sweetgum.

Mycorrhizal fungi also can be substituted for copper fertilizer in the culture of citrus seedlings (97). Other data has shown that mycorrhizal fungi can be substituted for zinc fertilizer in the greenhouse culture of citrus and even nitrogen fertilization can be reduced by as much as 300 percent in the presence of mycorrhizae (Menge, et al., unpublished data). This nitrogen savings effect is probably due to an increased efficiency of nitrogen use resulting from improved phosphorus nutrition of the plant.

Since mycorrhizal fungi are present in most soils, their unique fertilizer-absorbing abilities are normally already being used by most crops. If mycorrhizal fungi are removed or damaged in any way, then the amount of fertilizer required by a crop increases enormously. This is demonstrated by reports that citrus grown in fumigated soil or in hydroponic solutions often require massive phosphorus applications for adequate growth compared to field grown citrus (55). Citrus in the field can absorb phos-

phorus from phosphorus-deficient soils more efficiently than either corn or tomatoes, and citrus orchards do not normally require phosphorus fertilization (9). Differences in phosphorus absorption by citrus grown in fumigated soil and citrus grown in nonfumigated soils can be reconciled if mycorrhizal fungi, which are present in nearly all citrus orchards (52), are the equivalent of 100 to 500 pounds phosphorus per acre.

When and if the cost of fertilizer becomes exorbitant, we must devise the most efficient fertilizer supply systems possible—to minimize costs while conserving energy and nonrenewable resources. I submit that mycorrhizal fungi could be one alternative that might increase crop yields and yet reduce fertilizer costs and energy demands.

CURRENT COMMERCIAL USE OF MYCORRHIZAL FUNGI

Although nearly all plants require mycorrhizal fungi for maximum growth, the widespread occurrence of these fungi in nearly all soils limits the immediate needs for inoculation with mycorrhizal fungi. Mycorrhizal fungi are currently commercially usable in only three major agricultural areas: 1) disturbed sites, 2) fumigated soils, 3) greenhouses.

Disturbed Sites

Mycorrhizal fungi have been conclusively shown to improve revegetation of coal spoils, strip mines, waste areas, road sites, and other disturbed areas (18,19,15,49,81). In these stressed sites, mycorrhizal fungi are usually lacking and adding mycorrhizal fungi provides a nutritional advantage to associated plants in addition to providing possible resistance to low pH, heavy metal toxicants, and high temperature.

Fumigated or Chemically Treated Sites

Fumigation with biocides or pesticides such as methyl bromide (56), chloropicrin (72), dazomet (50), 1,3-D (72), vapam (71), and vorlex (71) may destroy or inhibit root infection by mycorrhizal fungi. Application of many soil fungicides such as arasan (71), banzot (95), benomyl (96), botran (71), carbofuran (3), chloramformethane (37), dichlofluanid (37), ethirimol (37), lanstan (71), mylone (71), PCNB (96), sodium azide (3), thiabendazole (37), thiram (96), triademifon (37), tridemorph (37), and vitavax (96) have also been reported to be harmful to mycorrhizal development. Flooding, planting non-mycorrhizal crops, or removing topsoil, may also reduce the population of mycorrhizal fungi to a level requiring reinoculation (7,78).

Fumigation with the biocide methyl bromide to remove soil-borne pests is required by regulation for the production of many nursery crops. It is also regularly used in many field agricultural situations. This chemical is extremely toxic to mycorrhizal fungi and most field fumigations are sufficient to destroy the native mycorrhizal inoculum (56). Stunting of crops following fumigation with methyl bromide is common and is due to the destruction of mycorrhizal fungi. Although a relatively small amount of land is treated with this chemical, less than 100,000 acres annually in the United States, stunting following fumigation with methyl bromide has been reported in the United States, Africa, Spain, Peru, Venezuela, and many other countries (52). Crops that are routinely grown in methyl bromide fumigated soils include strawberries, tomatoes, tobacco, nursery crops, tree crop replants, and some vegetable crops. For many of these crops the addition of mycorrhizal fungi following fumigation with methyl bromide is not only recommended but is imperative.

It appears that inoculating methyl bromide fumigated crops is economically possible. The cost for inoculating nursery-grown citrus with mycorrhizal fungi is about $288/acre, while the cost for phosphorus fertilizer alone is $338/acre. Fumigated tomatoes receive $51 worth

of phosphorus per acre while the cost for mycorrhizal inoculation is less than $28/acre. Mycorrhizal fungi can provide additional benefits to the crop other than just improved phosphorus nutrition.

For nursery plants grown in methyl bromide fumigated soil, inoculation with mycorrhizal fungi should be imperative for the following reasons:

- the plants grow better (prevents stunting following fumigation);
- there is a decreased need for fertilization, specifically phosphorus, zinc, and copper, resulting in decreased fertilizer cost and energy conservation;
- there is decreased chance for water stress and therefore reduced transplant injury;
- mycorrhizal plants survive better especially if transplanted to fumigated, poorly fertilized, or disturbed soil;
- plants will be inoculated with effective mycorrhizal fungi rather than leaving mycorrhizal infection to chance; and
- mycorrhizal plants may be more resistant or tolerant to some plant diseases.

Greenhouses

Greenhouse culture uses growth media such as pine bark, vermiculite, perlite, builders sand, and peat moss and these are devoid of mycorrhizal fungi. In addition, most greenhouse operators steam, pasteurize, or chemically treat their mixes to eradicate harmful pathogens. Nurserymen have compensated for the absence of beneficial mycorrhizal fungi by applying luxury amounts of fertilizer and water to achieve desired growth. Inoculation of container grown plants to reduce irrigation, fertilizer, and pesticide applications and cost can be done as demonstrated by Chatfield, et al. (10), Linderman (46), and Crews, et al. (12).

COMMERCIAL PRODUCTION AND INOCULATION WITH MYCORRHIZAL FUNGI

Many ectomycorrhizal fungi can be readily cultured on artificial media and inoculum can be grown under standard laboratory conditions (49). Experimentally, sterilized vermiculite and peat moss is frequently saturated with a liquid nutrient medium (49) and is infested with a desirable ectomycorrhizal fungus. Ectomycorrhizal fungi generally grow quite slowly and may take several months to colonize the vermiculite-peat moss mixture. This material can be used on a small scale to inoculate nurseries and greenhouses with mycorrhizal fungi. Abbott Laboratories, North Chicago, Illinois, has produced massive amounts of inoculum of the ectomycorrhizal fungus *Pisolithus tinctorius* (86). Abbott Laboratories produced the peat moss-vermiculite-nutrient solution inoculum under large-scale commercial conditions using commercial fermenters.

Under the direction of D. H. Marx, the U.S. Forestry Service has undertaken a massive testing program using the commercially produced inoculum. The inoculum will be tested in nearly 100 tree nursery test sites throughout the United States. Results will be available within 4 years and will indicate the commercial feasibility of producing and using mycorrhizal inoculum in fumigated tree nurseries.

Ectomycorrhizal inoculum can best be applied in the nursery. Once the trees become infected, the benefits can be transferred to wherever the trees are grown. In the nursery, mycorrhizal inoculum can be distributed by hand and rototilled into the soil before planting seed. Special machinery has already been built and is being used to incorporate ectomycorrhizal inoculum.

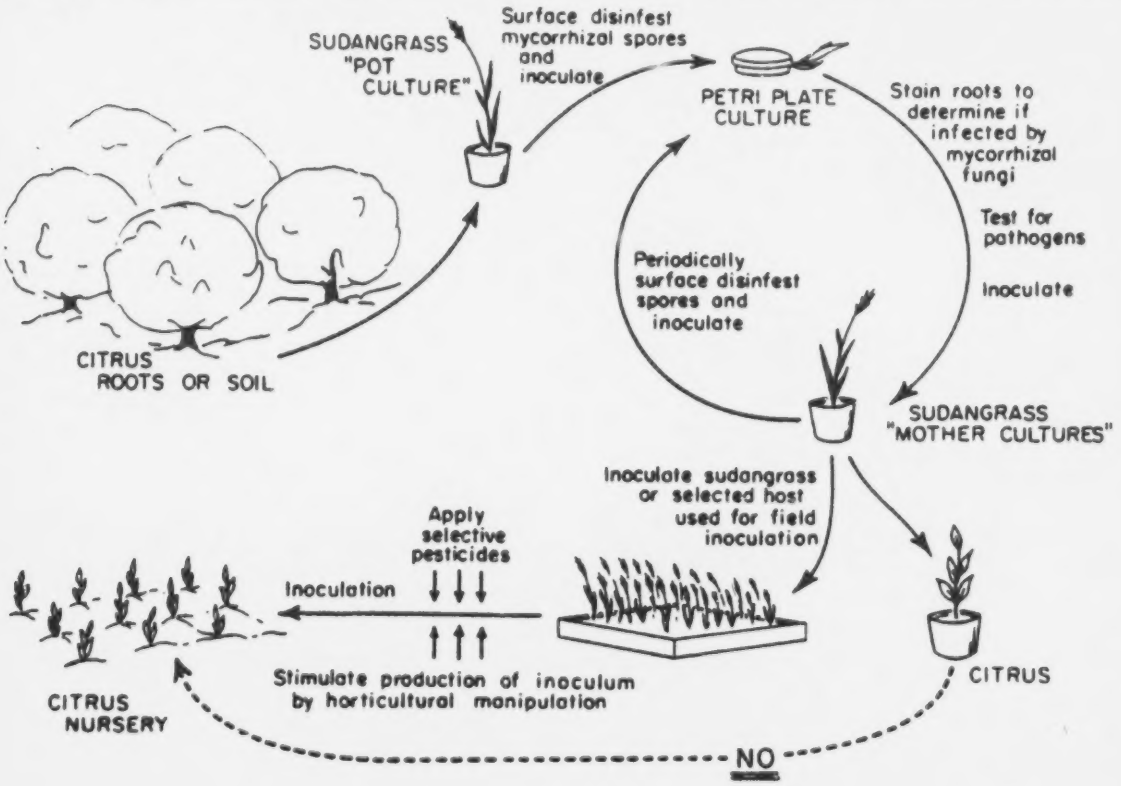
Commercial production of mycorrhizal inoculum for use in sterilized or fumigated soil is being attempted at several locations in the United States. Currently, the only way to produce suitable quantities of a mycorrhizal inoculum is on roots of susceptible host plants.

The possibility of pathogenic organisms contaminating mycorrhizal inoculum is an extremely serious problem when growing VA mycorrhizal inoculum in semi-sterile cultures in the greenhouse. For this reason, many scientists will consider mass production of VA mycorrhizal fungi only if it is done axenically (one organism only).

Realistically, however, not only must these obligate parasites be grown in vitro, but they must produce large quantities of spores in culture which will survive under soil conditions and infect plants in nature. Information gained from the culture of other formerly obligate parasites suggests that the possibility of realizing this goal in the near future is unlikely. Even if mycorrhizal fungi are cultured axenically, mycorrhizal inoculum for field use will probably be produced on the roots of suitable host plants.

With proper safeguards, mycorrhizal inoculum, free of plant pathogens, can be produced on plants in the greenhouse. Figure 5 illustrates a proposed scheme for producing mycorrhizal inoculum (53). VA mycorrhizal fungi can be isolated by using bits of roots or soil from the field to inoculate roots of "trap plants" growing in sterilized soil in the greenhouse. Sudangrass (*Sorghum vulgare* Pers.) is frequently used, but other plants such as tomato, soybean, corn, and safflower may be equally suitable. The soil used throughout is a low nutrient sand fertilized once per week with one-half the standard Hoagland's solution minus phosphorus. After production of VA mycorrhizal spores in the "pot cultures," the spores can be

Figure 5.—Proposed Scheme for the Commercial Production of Vesicular-Arbuscular Mycorrhizal Inoculum



removed by wet sieving (29), elutriation (25), or centrifugation (85). These spores must be surface disinfested with substances such as chloroamine T or sodium hypochlorite and streptomycin to assure that pathogens do not accompany the spores (68).

These surface disinfested spores are used to inoculate the roots of plants that were germinated and grown under aseptic conditions in growth chambers. The containers illustrated are made from plastic petri plates and filled with the low nutrient sand. After 1 to 4 weeks when the mycorrhizal fungi have infected roots grown under aseptic conditions root pieces can be removed and stained (73) to observe infection, root pieces are carefully removed and used to infect suitable host plants grown in sterilized soil in the greenhouse. Similar root pieces can be removed, examined, and plated on agar to observe pathogenic organisms.

If no pathogens are observed, the greenhouse "pot culture" may be used as a "mother culture" to produce inoculum that will be used in the field. Inoculum should be produced on selected hosts that have no root diseases in common with the host plant for which the inoculum is intended. For instance, inoculum for citrus could be produced on sudangrass but never on citrus. In this way the wide host range of most VA mycorrhizal fungi can be used. As another precaution against propagating pathogens along with mycorrhizal inoculum, the field inoculum should be drenched several times with pesticides chosen to eliminate pathogens known to infect the host for which the inoculum is intended. Mycorrhizal inoculum intended for citrus should be drenched with a nematicide to control the citrus nematode and fungicides to control *Phytophthora* and *Rhizoctonia*. Suggested pesticides are Ethazole and PCNB. PCNB reduces the population of mycorrhizal spores but the other pesticide can actually increase spore production (57). Several other pesticides can be used without harming mycorrhizal fungi (96).

Horticultural practices also could be used at this point to maximize spore production. Eliminating fertilization and slowly reducing the water may be effective in increasing spore production. When spores are mature, plant tops are removed and roots, soil, and spores can be ground up and partially dried (7 to 20 percent moisture content) and stored at 4° C until used. If concentrated spore suspensions are desired, spores can be concentrated by wet sieving (38), elutriation (25), or centrifugation (85) before storage. VA mycorrhizal inoculum can be freeze-dried if desired (38). Inoculum produced in this manner should be consistently infective and yet pathogen free.

Using the method described above, the estimated costs for producing mycorrhizal inoculum are shown in table 1. These figures are derived from production costs of a foliage plant greenhouse and could be reduced considerably

Table 1.—Estimated Cost of Production of Vesicular-Arbuscular Mycorrhizal Inoculum on Sudangrass in 4 Inch Pots

Item	Cost/pot
1. Labor:	
a. to prepare the soil mix	$0.03
b. potting, inoculating, and seeding	0.05
c. moving pots to growing area	0.03
d. pruning	0.02
e. spraying (insecticides and fungicides)	0.03
f. watering	0.02
g. harvesting	0.01
h. grinding and packaging	0.03
i. quality control	0.02
j. maintenance of mother cultures	0.05
Labor cost	$0.29
2. Materials:	
a. pots 4'	$0.07
b. seed	0.002
c. fertilizer	0.02
d. shipping containers	0.025
e. insecticides and fungicides	0.03
Materials	$0.147
3. Overhead expenses:	
a. heat	$0.08
b. depreciation on greenhouse	0.008
c. depreciation on boilers	0.003
d. maintenance allowance	0.006
e. office supplies	0.002
f. management and office work	0.03
g. return on investment	0.01
h. loss due to undeveloped plants	0.001
i. taxes	0.06
j. laboratory, incubator, etc.	0.04
Total for overhead	$0.24
Total cost $0.677	
Selling price $0.90	
0.18¢/500 spores	

since mycorrhizal inoculum quality is of importance and not plant quality. A reasonably generous estimate of the cost of mycorrhizal production, including technical labor and quality control, together with a small margin of profit, indicates that consumers may pay about 0.18¢/500 spores of VA mycorrhizal fungi. Such a cost could reasonably be borne by consumers such as greenhouse operators or nurserymen.

A similar method to that outlined above has been patented in England and is being perfected for large-scale commercial use (34). In this method plants are grown in peat blocks that are standing in a shallow nutrient-flow culture. After VA mycorrhizal spores are produced in the peat blocks they are ground up, roots and all, for inoculation. The finished product is not only excellent mycorrhizal inoculum but is light and easy to ship.

Although many methods have been used to inoculate plants with VA mycorrhizal fungi in greenhouse trials, few inoculation methods are acceptable for large-scale commercial inoculation. Several different methods to inoculate corn have been studied and layering inoculum under the seed was superior to seed inoculation or banding the inoculum (38). Hall (30) developed a method for pelleting seed with a mycorrhizal infection and determined that mycorrhizal fungi could survive up to 28 days under these conditions. Menge, et al. (53), found that layering inoculum below the seed and banding inoculum were superior to seed inoculations. Crush and Pattison (14) experimented with several means of inoculating seeds with VA mycorrhizal fungi, but again found that sowing seed above pelleted mychorrhizal inoculum was the most effective method for obtaining mycorrhizal infection. Hattingh and Gerdemann (31) reported growth responses of citrus in a fumigated nursery after inoculating citrus seed with mycorrhizal inoculum. Gaunt (26) inoculated onion and tomato seeds with a VA mycorrhizal fungus and reported that seed inoculated plants grew as well as plants that were inoculated by mixing VA mycorrhizal inoculum into the soil. Commercial applications of mycorrhizal inoculum using fertilizer banding machinery were successfully carried out in citrus nurseries in California (23).

Commercial VA mycorrhizal inoculum is produced using the method described above in two citrus nurseries—Brokaw Nursery, Saticoy California and the Thermal Ranch, Thermal, California. Experimental VA mycorrhizal inoculum is being produced and distributed on a large scale by Abbott Laboratories, North Chicago, Illinois. Other major corporations that are supporting or carrying out research on VA mycorrhizal fungi include Dow Chemical Co., Rohm & Haas Co., Dupont, Monsanto Co., and Ceiba-Geigy Chemical Co.

Plants growing in all soils do not respond favorably to VA mycorrhizal inoculum. If soil nutrition is optimum, mycorrhizal fungi will not enhance growth of plants. A method for detecting which soils require mycorrhizae for maximum production of citrus was devised by Menge, et al. (58). In soils with less than 34 ppm available P (Olson analysis), 12 ppm available Zn, 27 ppm available Mn, or 3 percent organic matter, citrus trees will probably require mycorrhizal fungi for maximum growth. Mycorrhizal inoculations are recommended only in soils with these characteristics. It is estimated that this includes approximately 85 percent of the southern California citrus soils. Similar studies could be done with other crops to determine which soils require mycorrhizal infestation.

POTENTIAL USES FOR MYCORRHIZAL FUNGI

Because mycorrhizal fungi occur on most agronomic crop plants and improve the growth of these plants, the potential use of these fungi as commercial "biotic fertilizers" is enormous. Large-scale field inoculations with mycorrhizal fungi are rare because of limited inoculum, and natural field soils usually contain adequate populations of indigenous mycorrhizal fungi.

Under these conditions, any growth benefit due to mycorrhizal inoculation would depend primarily on the superiority and/or placement of the mycorrhizal inoculum. Beneficial responses under these conditions would be predicted to be far less than the responses obtained in fumigated or partially sterilized soil. However, greenhouse and field experiments in which plants were inoculated with mycorrhizal fungi in nonfumigated soils have demonstrated that growth responses due to mycorrhizal fungi can occur under these circumstances.

In greenhouse experiments, using untreated soil, Mosse and her colleagues (62,63,65,67,70) demonstrated that preinoculation with mycorrhizal fungi could provide the following growth increases:

Crop	*Growth increase*
Centrosema spp.	34 percent
corn	306 percent
Melinis spp.	41-60 percent
onions	48-3155 percent
strawberries	250 percent
Stylosanthes spp.	85-88 percent
sweetgum	45 percent
Viola spp.	527 percent

Other studies have noted similar growth increases in untreated soil:

corn	14 percent	(Gerdemann, 1964)
corn	0-53 percent	(Jackson, et al., 1972)
mahogany	151 percent	(Redhead, 1975)
sudangrass	0-18 percent	(Jackson, et al., 1972)
white clover	80-100 percent	(Powell, 1977)

In a large-scale field experiment conducted in nonsterile, virgin, infertile fields, wheat preinoculated with a mycorrhizal fungus produced 220 percent more grain than non-mycorrhizal wheat (41). In a similar experiment (40), corn inoculated with a mycorrhizal fungus was 122 percent larger than non-mycorrhizal corn. Hayman (33) reported white clover growth increases in the field due to inoculation with a mycorrhizal fungus. Black and Tinker, in an extremely well-documented field experiment, found that fallow field inoculation with a mycorrhizal fungus increased potato yield 20 percent.

Not all mycorrhizal inoculations in nonsterile soil result in increased growth. Hayman (33) indicated that mycorrhizal fungi did not stimulate growth of white clover at several locations. Powell (75) obtained significant growth increases of white clover after inoculation with mycorrhizal fungi in only three of nine sites. Jackson, et al. (38), indicated that with certain mycorrhizal inoculation methods, growth of corn, sudangrass, and soybeans was not stimulated in nonsterile soil. Mosse (65) obtained significant growth responses of *Stylosanthes* spp. due to mycorrhizae in 6 of 11 nonsterile soils. Ross and Harper (85) reported no growth stimulation of soybeans in nonsterile soil.

Mosse (65) indicated that the inoculum potential of indigenous mycorrhizal fungi is the major determinant governing growth responses of plants to mycorrhizal fungi in nontreated soil. Powell (75) indicated that many indigenous mycorrhizal fungi are "inefficient" symbionts, and that inoculation by more efficient mycorrhizal fungi will result in growth increases even in nonsterile soil that contain high populations of "inefficient" mycorrhizal fungi. Placement of mycorrhizal inoculum is equally important in affecting a plant growth response (38). Certainly, plants infected early in the growing season by mycorrhizal fungi are better than plants that do not become infected until later (82).

Huge expanses of tropical soils (e.g., the Brazilian Cerrado) are either deficient in phosphorus or immobilize phosphorus fertilizers. These marginal agricultural lands could be productive if mycorrhizal fungi, with the ability to efficiently use extremely small quantities of fertilizer, were developed and added to the soil. Cheap but readily available rock phosphate could be added as the phosphorus source. This phosphorus source is a poor fertilizer but releases small quantities of phosphorus for long periods of time. Some mycorrhizal fungi use rock phosphate much better than others and can tremendously improve growth of plants growing in poor soils fertilized with this material (59,66).

Mycorrhizal fungi have been proposed as unstable soil or sand dune stabilizers (96). Finally ectomycorrhizal fungi have been shown to improve rooting of a wide variety of non-host plants and the possibility of using them as a commercial root stimulant has been proposed (45).

CONSTRAINTS ON THE COMMERCIAL USE OF MYCORRHIZAL FUNGI

The current major obstacles to the commercial use of mycorrhizal fungi are:

- the lack of large-scale field experiments under normal agricultural conditions,
- the lack of cost-benefit analysis to determine the economics of mycorrhizal applications, and
- the trend toward excessive fertilization to substitute for the lack of mycorrhizal fungi.

Perhaps the most important deterrent of commercial use of mycorrhizal fungi is the lack of large-scale field tests in a variety of agricultural soils and locations. The program initiated by D. H. Marx and the U.S. Forest Service will correct this deficiency for ectomycorrhizal fungi and within 4 years it will be known if these mycorrhizal fungi will indeed be economically feasible to use on a wide scale in the production of forest trees.

This type of program remains to be established for VA mycorrhizal fungi. Without such data it is difficult to establish a potential market for mycorrhizal inoculum. Without a market there is little incentive for industry to initiate the production of commercial inoculum. Without commercial inoculum it is difficult to carry out large-scale field tests. With the recent establishment of several commercial sources of mycorrhizal inoculum perhaps this cycle will be broken and more field tests will result.

Once large-scale field tests are seen to be successful, light-weight commercial mycorrhizal formulations will develop and new application methods will be devised. Most importantly, from large-scale field tests, cost benefit analysis can be accurately done to determine the economic benefit derived from the use of mycorrhizal fungi. In the end, this will be the determining factor in the commercial application of mycorrhizal fungi. Biological scientists are rarely able to critically assess the economic factors involved in the application of a new technique and I recommend that agricultural economists should be asked to participate in the cost-benefit assessment of VA mycorrhizal inoculation.

Heavy phosphorus fertilization severely inhibits mycorrhizal infections (17,68). More recently, it is becoming evident that heavy nitrogen and zinc applications are also inhibitory to mycorrhizal fungi (32,51). Daily applications of 100 ppm nitrogen under greenhouse conditions have been shown to completely eliminate mycorrhizal infections (J.A. Menge, unpublished data). Many commercial greenhouses add over 200 ppm nitrogen daily to their plants. In greenhouse and fumigated nursery conditions, growers are using excessive fertilization to substitute for the lack of mycorrhizal fungi. Under these conditions, not only do mycorrhizal fungi not benefit their host plants, but it is difficult to successfully establish mycorrhizal infections so that the plants will be mycorrhizal once they leave the supraoptimal fertility regime. As long as fertilizer is relatively available and not excessively expensive, it will take a major educational program to convince many growers to change their standard operating procedures and use mycorrhizal fungi that will not only be cheaper but will conserve fertilizer and energy.

In my opinion, granting agencies such as the National Science Foundation, Rockefeller Foundation, USDA competitive grants, and the Israeli-U.S. granting agency BARD have effectively provided adequate funding for basic mycorrhizal research. The number of scientific papers on mycorrhizal fungi has quadrupled since 1960, which is evidence that there is great interest and money available for basic mycorrhizal research. However, there are few agencies that will fund the final applied steps in a biological commercialization project. Research money for large-scale "applied" or "demonstration" experiments is unavailable. Funding for small-scale pilot projects is also not available. It remains for private industry to pick up the projects from this point, but they have been reluctant to do so. The transition is not going smoothly and seems to be proceeding slowly if at all.

EFFECTS OF MYCORRHIZAL FUNGI ON AGRICULTURE

It is very difficult for a scientist to speculate on the effects of a new procedure on the social and economic structure of an agricultural society. Frequently good ideas do not receive the acclaim they deserve because of prejudices, ignorance, religious preferences, social mores, and other reasons not fully understood by scientists. In my opinion, the effects of mycorrhizal technology would most alter the socioeconomic structure in areas of intensive agriculture. These situations would be more prevalent in agriculture in developed nations. Mycorrhizal fungi are most useful in reclaiming sites disturbed by heavily mechanized industries or soil fumigation. Mycorrhizal fungi can reduce energy and fertilizer and increase the efficiency of crops grown intensively. Therefore, mycorrhizal fungi can be viewed as conservation measures or as substitutes for high energy uses in developed nations.

In less developed nations, growers would have to be educated to the methods of producing, handling, and inoculating living microorganisms. This may be difficult. In countries with a less well-developed agricultural system, mycorrhizal fungi have not been altered and are probably functioning effectively and need not be applied under such conditions. Fertilizer in most underdeveloped countries is probably applied sparingly as manure and therefore mycorrhizal fungi will not result in a great savings either of fertilizer or energy.

If superior strains of mycorrhizal fungi are developed, marginal agricultural land could be made productive. Huge amounts of marginal agricultural land exists in Africa and South America and the proper use of this land may well decide the future of some countries. Increased use of agricultural land will provide for a greater economic base, larger agricultural productivity, and a better way of life for large populations in underdeveloped countries. Educating agriculturists to the importance of mycorrhizal fungi may allow developing countries to avoid the excessive use of energy, fumigants, and fertilizers associated with intensive agriculture.

CONCLUSIONS AND RECOMMENDATIONS

Mycorrhizal fungi may be one alternative that can immediately improve revegetation of disturbed sites, increase crop growth in fumigated soils and greenhouses, and yet reduce fertilizer costs and energy demands. If superior strains of mycorrhizal fungi were developed, they could potentially improve growth of nearly all agronomic crops in a wide variety of soils throughout the world. Both ectomycorrhizal fungi and vesicular-arbuscular mycorrhizal fungi are in commercial production on a small scale. The greatest obstacles to the commercialization of mycorrhizal fungi appears to be: 1) the lack of large-scale field tests under typical agricultural conditions in a variety of locations; 2) adequate cost-benefit analysis to determine the economics of the utilization of mycorrhizal fungi; and 3) a reluctance on the part of growers to switch from an energy dependent, heavy fertilizer system to a new, but cheaper, energy conservative system using mycorrhizal fungi.

Recommendations that could substantially increase the commercial use of mycorrhizal fungi (in relative order of importance) are as follows:

1. Improved availability of grant funds for large-scale field applications of mycorrhizal fungi in a wide variety of soils throughout the world. It would be useful to establish several pilot projects in various less developed countries. These pilot projects could produce and distribute mycorrhizal inoculum on a variety of crops growing under different soil conditions. Cost-benefit analysis on such projects could adequately assess the economics of inoculation with mycorrhizal fungi.

2. Funds should be made available to create a worldwide bank of beneficial mycorrhizal fungi. The establishment of such a facility is being investigated by the mycorrhizal community and the National Science Foundation has agreed to entertain a proposal for such a facility. The University of Florida has agreed to supply the facilities as well as substantial operating costs for such an establishment. A second idea would be to add the responsibility for maintaining mycorrhizal cultures to the already established government facility called the American Type Culture Collection which maintains many important fungal cultures.
3. It would be desirable to establish a USDA-supported vesicular-arbuscular mycorrhizal research center that would be responsible for maintaining and coordinating U.S. research on mycorrhizal fungi. This facility would complement the Mycorrhizal Institute in Athens, Georgia, which was created by the Forest Service to coordinate mycorrhizal research on forest trees.
4. A world survey should be conducted to collect and test as many different vesicular-arbuscular mycorrhizal species as possible. The discovery of a superior mycorrhizal strain with a wide host range could tremendously increase agricultural productivity throughout the world.
5. Research is necessary to elucidate the exact role of mycorrhizal fungi play in improving plant growth under stress conditions such as drought, salt, toxic soil materials, or in marginal agricultural lands.
6. Research is necessary to elucidate the genetics of mycorrhizal fungi. Virtually nothing is known on this subject. The ability to breed these organisms could result in tremendously increased agricultural productivity.
7. Efforts should be intensified to grow vesicular-arbuscular mycorrhizal fungi in the laboratory using artificial media. A breakthrough in this area could improve the feasibility of attaining all of the above recommendations. However, since scientists have been trying to artificially culture VA mycorrhizal fungi since 1900, this objective may be difficult to achieve and incentives to work on such a problem are difficult to justify.

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Chapter XI

A Low Fertilizer Use Approach to Increasing Tropical Food Production

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Contents

	Page
Abstract	207
The Tropics	207
Land Use	208
Farming Systems	208
Tropical Food Crops	209
Soil Fertility Concepts—A General Statement	209
Soil Acidity and Liming	210
Finding the Correct Lime Level	211
Nitrogen	212
Nitrogen Supply Process	212
Biological Nitrogen Fixation	213
Productivity of Improved Grass-Legume Mixtures	214
Nitrogen Release From Organic Matter	214
Phosphorus	215
Management of Phosphorus Fertilizer	215
Sources of Phosphorus	216
Sulfur Deficiency	217
Potassium Deficiency	218
Rice	218
Plants That Tolerate Adverse Conditions	219
References	221

Chapter XI

A Low Fertilizer Use Approach to Increasing Tropical Food Production

ABSTRACT

Low fertilizer use in the Tropics appears to be a desirable goal and it could involve several strategies aimed at increased crop production with minimal use of inputs.

According to the general response curve that shows the effects of added nutrients, the use of small amounts of an input may result in substantially increased production. The philosophy employed here is to use less than maximum inputs to achieve the highest output: input ratio or to make maximum use of inputs rather than to maximize yields. That often requires a much greater use of scarce inputs such as fertilizer, capital, etc.

Because they have inherent high fertility, limited inputs are needed on the "high base soils" (18 percent of tropical soils) when there is sufficient water. Small amounts of nitrogen, phosphorus, and/or micronutrients are sufficient. High yielding varieties should be used on these soils to take advantage of the naturally high soil fertility.

On the "low base soils" (51 percent of tropical soils), which have high soil acidity and aluminum and the associated phosphorus deficiency, the production package should be considerably different. Lime may be necessary to reduce the availability of toxic aluminum. This will also increase the availability of phosphorus. However, additional phosphorus and/or sulfur will probably be necessary to increase yields.

The use of crops that will tolerate adverse soil conditions should also be employed on these soils. This reverses the philosophy of changing the soil to fit the crop (an expensive procedure on these soils) to one that takes the soil as it is (or changes it minimally) and uses crops that grow well under existing conditions. Examples of such crops are upland rice, cassava, sweet potatoes, cowpeas, and some grass and legume pasture crops.

With both high and low base soils, nitrogen is probably the most limiting element. Low yields in many tropical areas reflect a low level of nitrogen availability. Low yields and the lack of nitrogen result in low levels of protein for local human consumption, causing malnutrition. An excellent source of protein and nitrogen are leguminous crops. These crops have the potential to biologically fix nitrogen from the atmosphere when growing in association with the correct bacteria. When these crops are used, the nitrogen input into the cropping system can be increased several fold. This technology is inexpensive, easy to use, and available. Most important, it can substantially increase the yield of crop plants as well as meat and milk production to the benefit of the small farmer and the landless poor.

THE TROPICS

The Tropics are that area of the world located between 23.5° north and south of the Equator. Thirty-eight percent of the Earth's land surface (about 5 billion hectares) and 45 percent of the world's population (about 1.8 billion people in 1975) live in this area. Most of the world's developing countries lie in the Tropics, although some areas in the Tropics are not considered developing and many developing countries are outside the zone.

Because of the proximity to the Equator, the Tropics experience little change in temperature during the year. Variation of daylength is also relatively small compared to temperate zones. Rainfall is the variable which differentiates tropical areas. About one-quarter of the Tropics, mostly those near the Equator, have a rainy climate. Seasonal climates—those with a distinct wet and dry period—cover about one-half of the Tropics. Dry climates, usually having a short wet season, cover 16 percent of the Tropics. Tropical deserts comprise the remaining area, about 11 percent.

In 1960, the world's population reached 3 billion; by 2000 6 billion will inhabit the Earth. Much of this population increase is taking place in the Tropics, primarily in Asia. This population explosion will place a much greater strain on the resources of the Tropics. Malnutrition, particularly protein deficiency, is widespread throughout the area. Protein deficiency, a lack of high protein food, is related to a lack of nitrogen in the soil-plant system.

Protein synthesis in the plant only occurs when there is sufficient nitrogen in the soils, therefore, a lack of soil nitrogen decreases the rate of protein production in plants and hence, in the food supply. Inexpensive and efficient means to increase nitrogen in the tropical system are known. Use of these simple technologies could increase protein production and eliminate much of the misery and suffering in the Tropics caused by poor nutrition.

LAND USE

About 10 percent of the tropics are cultivated for food production; pastures and meadows account for an additional 20 percent. The President's Science Advisory Committee estimated that only 500 million hectares were cropped in 1967 even though the potential for cultivation was 117 billion hectares. Grazing occupied 1 billion hectares, but the potential was 1.6 billion hectares. These figures indicate that there is much potential to expand in agricultural production in the Tropics.

The use of land will vary depending on soil factors, climate, economic, social, and political factors. In general, the farming systems are vastly different than those practiced in the United States.

FARMING SYSTEMS

Common farming systems in the Tropics are (56):

1. shifting cultivation, where the land is cropped and then abandoned when yields fall, covers 45 percent of the Tropics;
2. settled subsistence farming is practiced on 17 percent of the Tropics;
3. nomadic herding covers 14 percent of the area;
4. livestock ranching uses 11 percent; and
5. plantation systems, which cover 4 percent of the tropical area.

If food production is to be increased and the majority of people benefit, programs must be aimed at the small farm rural population since small farms are the most numerous. In tropical Asia, 75 percent of all farms are smaller than 2 hectares (5 acres) (36). Sixty-nine percent of Central American farms are smaller than 5 hectares (12 acres) (14). The average farm size of 20 tropical African countries reporting such data in the 1973 FAO Production Yearbook was 5.4 hectares. Studies by CATIE (14) and Pinchinat, et al. (53), showed that about 70 percent of the food consumed in Colombia

and Central America is produced on small farms. Therefore, any strategy dealing with food production in the Tropics must deal with the small farmer.

TROPICAL FOOD CROPS

Common tropical crops are sugarcane, pineapple, bananas, coffee, and tea. These crops, however, contribute little to the nutrition of people in the Tropics because they are exported, largely to the temperate zone. The major food crops consumed by tropical people are rice, cassava (root crop), corn, sweet potatoes, yams, wheat, sorghum, peanuts, potatoes, and dry beans (in order of decreasing importance). The total area cultivated for these 12 crops is only 300 million hectares compared to 1 billion hectares of pasture and meadow.

The Tropics can be characterized as a region where population pressures are often highest and likely to remain that way in the near future. But on the positive side, the soils and climate provide a resource base that can expand production and help meet these food needs. The introduction of simple technologies could greatly increase food production, helping to stabilize these countries in many ways.

Much of this increase must come from a better use and understanding of the tropical soils' capacity to produce. Therefore, the bottom line question becomes a question of soil fertility.

SOIL FERTILITY CONCEPTS—A GENERAL STATEMENT

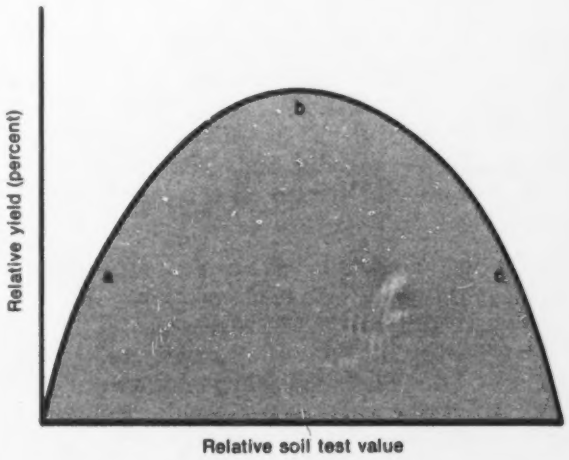
A fertile soil has the capacity to produce a high yielding and high quality crop. More specifically, it is a soil that does not limit production because of physical, chemical, or biological constraints.

Numerous essential elements are required for crop production, including carbon, hydrogen, oxygen, nitrogen, phosphorus, potassium, calcium, magnesium, sulfur, iron, copper, boron, zinc, manganese, and molybdenum. The first three are obtained from water and the carbon dioxide in the atmosphere. The rest must be taken up from the soil by the plant's root system. Another important element is aluminum. Although not considered essential to growth, if excessive, it is severely toxic to plants and can reduce plant growth and crop yield.

Soil tests attempt to predict crop yield for a number of elements. These tests determine as nearly as possible the soil's capacity to supply the elements necessary for plant growth. Where the soil's supply is considered insufficient for a desired yield, additional amendments are supplied to the soil increasing its "fertility," or ability to produce.

A typical soil test crop response curve follows:

The response curve has three general areas. Area "a" is the part of the curve where small inputs of nutrients result in increasingly great-



er production, i.e., the output:input ratio is favorable. Area "b" is a relative plateau where increasing fertilizer inputs do not result in increasing yields and the output:input ratio is poor since yield can be maximized at a lessor input rate. Area "c" represents the portion of the curve where additional nutrients actually reduce yield because of excessive or toxic concentrations. Obviously this is a situation to be avoided. This is the situation with aluminum in many unlimed soils of the Tropics.

A few simple equations help to explain the relationship between the soil and plant nutrients. The general relationship between elements in the soil and plants may be seen in the following, where E represents an element used in plant growth.

$$\text{Soil solid phase}_{(E)} \qquad \text{Soil solution phase}_{(E)}$$
$$\text{Plant root}_{(E)} \qquad \text{Plant top}_{(E)}$$

As the above equation indicates, an element is taken in by plant roots and moved to the plant top as a soluble element dissolved in the soil solution. Elements are generally considered to be available when they are in the solution phase of the soil. In many instances an element is unavailable to the plant because it is not in a form the plant can use, that is, not in solution. Another equation helps to explain the soil fertility-plant nutrition relationship. Again, E represents an element necessary for plant growth.

$$\text{Unavailable}_{(E)} \qquad \text{Available}_{(E)}$$

This simple equation shows the equilibrium in the soil that determines if the nutrient can be used by a plant. This equilibrium is controlled by the soil environment: soil pH, micro-organisms, oxygen, water, temperature.

SOIL ACIDITY AND LIMING

Soil pH is a term used to delineate the relative acidity or alkalinity of soils. It is important because soil pH affects the availability of most nutrients. The soil pH scale follows:

1 2 3 4 5 6	7	8 9 10 11 12 13 14
More acid	Neutral	More alkaline or basic

Early in history, man learned to cultivate high base soils (soils high in calcium, magnesium, and potassium and low in aluminum) because they are naturally more productive. The majority of cultivated soils of the Tropics are not acid (56), although the majority of soils of the humid Tropics are acid. Soils of tropical America are more acid than those of tropical Africa and Asia.

Liming of acid soils has been a longstanding practice. For a long time, the practice involved adding sufficient lime to raise the soil pH to 7 (neutrality). However, in the early 1950s soil chemists showed that exchangeable aluminum, toxic to plants, was the predominate element in acid mineral soils as contrasted to organic soils (18). Exchangeable elements such as calcium, magnesium, and potassium are positively charged and are held in the soil by negatively charged sites. Strongly acid soils (pH less than 5.0) favor aluminum availability to plants, whereas above pH 5.5, calcium, magnesium and potassium prevail.

High soil solution aluminum, the available form for plants, causes reduced plant growth because aluminum is toxic to plants. Evans and Kamprath (25) found that an exchangeable aluminum saturation of 60 percent was required before a large amount of aluminum was present in the soil solution. Work in Guyana showed that an aluminum saturation of less than 60 percent resulted in less than 1 ppm—1 part per million—in the soil solution (13). Increasing fertilizer results in an increase of aluminum in the soil solution (34). Therefore, use of high amounts of fertilizer could increase aluminum toxicity if the soil is sufficiently acid. Available aluminum in the soil solution decreases with increasing organic matter since aluminum forms very strong complexes, making it unavailable.

Research by Kamprath (42) showed that elimination of all the exchangeable aluminum was not necessary to obtain maximum yield in field and greenhouse studies. Maximum yields of corn, soybeans, and cotton were achieved with aluminum saturation values of less than 45, 20 and 10 percent respectively where soil pH was low. Growth of sugarcane was severely depressed on a soil with an exchangeable aluminum saturation of 70 percent. Addition of lime to reduce the aluminum saturation to 30 percent resulted in a four-fold increase in sugarcane growth (1).

FINDING THE CORRECT LIME LEVEL

The work cited above, plus other work, has shown that lime should be added to reduce the toxic levels of aluminum. This results in a much lower soil pH and the use of much less lime than the traditional approach of liming to neutrality. Liming beyond this point has resulted in reduced yields on soils of the Tropics because of deficiencies of manganese, zinc, and/or iron. Like aluminum, manganese becomes available as the soil becomes more acid (7). Some soils are low in aluminum but high in manganese. In either case, liming will reduce the availability of manganese. However, since manganese is an essential element, liming must not be so high as to make the element unavailable and reduce the soils productivity.

A wise liming philosophy, therefore, should be to add sufficient lime to decrease the availability of aluminum without limiting manganese to the point of deficiency. The factors to be considered are: 1) the amount of lime needed to decrease the percent of aluminum saturation to a level where the particular crop and variety will grow well, 2) the quality of lime, and 3) the placement method (56). Kamprath (42) suggests that lime recommendations be based on the amount of exchangeable aluminum and that lime rates be calculated by multiplying the milliequivalents (meq) of aluminum by 1.5, to find the meq of calcium needed as lime. Lime rates calculated by this method neutralize 85 to 90 percent of the exchangeable aluminum in soils with 2 to 7 percent organic matter, which includes the majority of soils.

This method has been successfully used in Brazil since 1965 and is employed in most American countries. The application of this formula has reduced rates of liming substantially, particularly in acid, highly leached soils low in cation exchange capacity (this term refers to the amount of negatively charged sites in the soil). In most cases where 1 to 3 meq of exchangeable aluminum is present, lime applications are now on the order of 1.6 to 5 tons per hectare. In the past, rates of 10 to 30 tons per hectare were frequently used with mixed results.

Different crops tolerate different levels of aluminum. Crops such as cotton, sorghum, and alfalfa are susceptible to levels of 10 to 20 percent aluminum saturation, therefore, liming should be aimed at zero aluminum for these crops. Corn is sensitive to 40 to 60 percent aluminum saturation, therefore, 20 percent aluminum saturation could be more economical for corn. Other crops such as rice and cowpeas are more tolerant than corn. Coffee, pineapple, and some pasture species seldom respond to lime, even in soils with high aluminum saturation.

Sources of lime are difficult to find in the Tropics. If possible, lime should contain both calcium and magnesium. The coarseness of the lime also affects its usefulness. Coarse lime, that which does not pass through a 20 mesh sieve, will have very little reactivity; lime that passes through a 60 mesh sieve will react very slowly. Fine lime, which passes a 100 mesh sieve, will react quickly. Generally, a good grade of fineness is more than 60 mesh; a better grade is 100 mesh. Lime is commonly mixed in the top 6 to 8 inches of soil. In Puerto Rico,

Abruna, et al. (2), observed no differences in pasture yields between surface-applied and soil-incorporated lime.

When very acid leached soils are limed to pH 5.5, most of the root development occurs in the topsoil. The highly toxic aluminum in the subsoil prevents deeper root development. In such cases, plants suffer from water stress during short-term droughts even though the subsoil is still moist. Studies show that deep placement of lime resulted in deeper root development, diminished water stress during drought, and increased corn yield of 20 to 25 percent (56).

NITROGEN

Nitrogen, too, is very crucial to crop production and the availability of protein to tropical people. Acid soils contribute to that problem largely because soil acidity reduces nitrogen fixation by leguminous plants. In nitrogen fixation, the nitrogen of the atmosphere is made available to plants. Next to water, nitrogen is the most limiting factor in crop production in the Tropics. It is necessary for protein synthesis and production. Plant-available nitrogen is derived from organic matter, leguminous nitrogen fixation, fertilizers, and animal manure. The main source of nitrogen in the Tropics is the decomposition of organic matter. Therefore, practices that maintain organic matter in the soil are essential. Organic matter not only provides nitrogen, but it improves the soil's physical condition and water-holding capacity, increasing water to plants and decreasing the soil temperature.

NITROGEN SUPPLY PROCESS

Nature has provided the nitrogen for crop production since the beginning of time through natural processes. However, seldom has it provided an abundance of nitrogen for long and sustained periods of crop production on the same piece of land. Moreover, natural processes at their best have seldom provided enough plant-available nitrogen to achieve the level of food and fiber production needed to meet the demands of present day crop production. Natural nitrogen-supplying processes include: 1) mineralization of nitrogen from soil organic matter and from crop residues; 2) the reverse process of immobilization in the decomposition of plant and animal debris and soil organic matter; 3) fixation of nitrogen from the atmosphere, largely through biological processes; 4) addition of nitrogen through rain and other forms of precipitation (5).

The nitrogen in soil organic matter is important for crop production. However, soil nitrogen is not inexhaustible; it declines in quantity in the soil as it is used by crops grown, harvested, and consumed. Nitrogen in soil is largely organic, replenished by periodic additions of fresh plant or animal residues.

Under normal conditions, nitrogen is added to the organic supply in soil each year through crop residues (immobilization), but it is unavailable to plants. Also through biological decomposition, organic nitrogen in the soil is continuously converted to the inorganic form (mineralization), which is available to plants. Under any sustained system of crop and soil management, these two processes tend to approach each other in magnitude so that mineralization balances immobilization (9). When this balance is attained, the system is considered to be in equilibrium.

The implications and consequences of an equilibrium in the soil's organic nitrogen need to be emphasized. At equilibrium, the amount added to the supply of organic nitrogen is essentially balanced by a like amount of decomposition. The total quantity of soil nitrogen re-

mains unchanged and the net amount that can be and is supplied to a crop is zero (5). During periods of virgin or noncultivated conditions, such as a forest, certain soils tend to build up organic matter, accumulating as much as 10,000 kg/ha of nitrogen under virgin conditions. During the first years of cultivation, these same soils may supply as much as 400 kg/ha of available ntirogen per year to crops (59). As cultivation continues and the organic nitrogen declines, the quantity of nitrogen becoming available each year also declines. After long periods of cultivation, the soil's organic matter becomes exhausted unless legumes are grown or the soil fertilized with nitrogen. A minimal amount of nitrogen is supplied by rainwater and nonsymbiotic nitrogen fixation.

Many of the major land areas of the Tropics have now been cropped for extended periods and the organic matter stored under virgin conditions has been dissipated. With little or no use of nitrogen fertilizer, tropical crop yields reflect the paucity of the natural nitrogen supply from rainwater and nonsymbiotic nitrogen fixation.

Yields of corn of 600 to 1200 kg/ha and of wheat of 400 to 800 kg/ha require a nitrogen supply only a little larger than could be expected from rain and from nonsymbiotic fixation. Yields this poor remove no more than 15 kg/ha of nitrogen from the land in the harvested grain products. Such minimal yields can be sustained for a long period of time without fertilizer or legumes, but do little to sustain the protein needs of animals or humans.

However, with inclusion of legumes in the rotation either as a primary food crop or as a green manure, the nitrogen supply in the soil-plant system can be increased substantially. This will result in increased crop and protein production, helping to meet the primary malnutrition problem of the Tropics.

BIOLOGICAL NITROGEN FIXATION

Despite the great use of chemical fertilizer today, biological nitrogen fixation processes have been responsible for providing most of the nitrogen currently used by and tied up in plants and animals and in the decomposed residues found in soil. It supplies the major part of the nitrogen for crop production in world agriculture.

According to reviews by Henzell and Norris (37) and Jones (40), *Rhizobium* bacteria fixation accounts for 100 to 300 kg of nitrogen per hectare and year. Whitney (67), however, reports an annual range of 47 to 905 kg of nitrogen per hectare for pure stands of an improved variety of *Leucaena leucocephala.*

Obviously, the potential to increase the nitrogen in a cropping system several fold (15 kg/ha v. several hundred kg) using legumes in crops or pastures is possible. Differences among adapted species within a specific environment seem to be closely related to dry matter production (total growth) (40). This suggests that there is little difference in the capacity of legumes to fix nitrogen as long as they are adapted to the environment. Factors affecting dry matter production, such as moisture or nutrient stress, solar radiation, diseases, and other factors will determine nitrogen fixation.

Pastures and meadows make up the greatest portion of the land that is managed for food consumption, therefore, potential increases in food are large if this segment of tropical production could be increased. Another important factor to consider is that production from pastures and meadows results in increased meat and milk, both high in quality proteins.

Some individuals consider cattle to be a very inefficient source of protein for humans in the food chain. This is true when animals and humans compete for grain. It is not true when cattle convert forage from pasture and meadow lands into meat and milk. The determining factor will be how much and what kind of land is available for cultivation.

PRODUCTIVITY OF IMPROVED GRASS-LEGUME MIXTURES

Beef production will normally increase by a factor of 2 to 4 due to establishment of grass-legume mixtures (40). Few experiments provide long-term data. Sanchez (56) cites a study of a legume, *Stylosanthes humilis* introduced into a Queensland pasture and followed beef production for 7 years. The following table summarizes the results:

Beef Production Systems in the Tropics

Treatment	*Beef kg/ha*
Grass alone	24
Grass & fertilization*	62
Grass & legume	93
Grass & legume & fertilization*	148

*Annual application 10 kg P/ha as 0-20-0 and 40 kg K/ha plus Mo.

It is interesting to note that the grass-legume treatment produced more beef than did the fertilizer treatment. The grass-legume mixture plus fertilizer more than doubled the beef produced by grass alone plus fertilizer, demonstrating the effect of adding nitrogen to the system via the legume.

Another plant, a fern, Azolla, grows in association with rice, the major crop of Asia. Azolla does not fix nitrogen itself, however, it grows in symbiotic association with blue-green algae *Anabaena azollae* (16). About 10 percent of China's rice (3.2 million acres) are grown with Azolla. He states that yields of rice of 6 tons per acre have been reported along with 60 tons of Azolla. Rice with conventional fertilizers yields about 4 tons per acre. Preliminary experiments indicate that Azolla will produce 50 to 180 pounds of nitrogen per acre, making it highly attractive as a natural nitrogen source.

Another nitrogen fixing system has been reported by Dobereiner and her associates in Brazil (20,22). Their work has focused on nitrogen fixation by nonleguminous plants. This work has a great potential if efficient strains of bacteria can be found. At present, this rate of asymbiotic fixation contributes only about 10 kg of nitrogen per hectare per year.

Recent evidence suggests that symbiotic nitrogen fixation takes place in some tropical grasses (22). The nitrogen fixation takes place in the rhizosphere (soil close to root), however, since this nitrogen is taken up directly by plants, it is considered symbiosis. Laboratory experiments suggest that the magnitude of this mechanism may be on the order of 1 kg of nitrogen per hectare per day. This system needs to be taken out into the field to determine nitrogen fixation under more realistic conditions.

Field beans, *Phaseolus vulgaris,* a staple in many Latin American countries, appear to fix little nitrogen (56). This is attributed to poor nodulation characteristics that may be due to low phosphorus or high aluminum which inhibit *Rhizobium* activity. When these legumes are grown, they contribute nitrogen to the system. It eventually becomes available via mineralization or the breakdown of complex nitrogen compounds into simpler nitrogen compounds.

NITROGEN RELEASE FROM ORGANIC MATTER

Plant-available inorganic nitrogen in most tropical areas shows a marked seasonal fluctuation (56). This is characterized by a slow nitrate (available form to plants) buildup during dry season. There is a large, but short-lived, increase at the beginning of the rainy season, and a rapid decrease during the rest of the rainy season because of leaching.

Since the level of plant-available nitrogen in many tropical soils is low, the use of extra nitrogen (green manure, animal waste, or fertilizer) will almost always increase yields of crops if these crops can make use of the extra nitrogen. Therefore, if nitrogen fertilizer is to be added, it should be at rates that can be justified economically.

Since most nitrogen fertilizer is very transitory due to its soluble nature, the use of nitrogen should be timed to the needs of the plant. This will avoid excessive loss due to leaching rain or denitrification, the loss of nitrogen as a gas. Numerous experiments in both temperate and tropical climates have shown that the application of nitrogen soon after planting, when demand is highest, will result in higher yields and more efficient use of the applied nitrogen.

Nitrogen loss is not a serious problem with organic nitrogen from legumes or animal waste since these complex organic materials are not subject to leaching like the more soluble inorganic fertilizers. This suggests that organic forms of nitrogen have a greater efficiency in high rainfall areas. In some cases, nitrogen addition alone will not increase productivity substantially because other elements may be deficient or toxic. This is the case with acid soils. Lime will promote legume establishment and growth by reducing aluminum availability and increasing the availability of phosphorus. Phosphorus deficiency is a serious problem in many tropical soils and must be considered in the fertility regime.

PHOSPHORUS

Following water and nitrogen, phosphorus is probably the most limiting nutrient in the Tropics. This is particularly true in the acid soils of the humid tropics since the high aluminum and iron concentrations render phosphorus unavailable to plants. The term used to denote this is phosphorus fixation. When phosphorus is added as soluble monocalcium phosphate ($Ca(H_2C9PO_4)_2$) the soil pH is reduced to 1 to 1.5 (very acid). The acid dissolves aluminum, iron, potassium, and magnesium compounds and unsoluble phosphates of iron and aluminum are formed. The higher the phosphorus-fixing capacity of the soil, the higher the content of iron and aluminum oxides (56). Higher exchangeable aluminum also increases the soil's phosphorus fixation ability. Because of the fixation process, higher rates of phosphorus must be added to achieve the same level of plant-available phosphorus compared to a soil that does not fix phosphorus. The amount of phosphorus added to a soil to get 0.2 ppm phosphorus (adequate level) in the soil solution can vary from 20 to 30 pounds per acre to as much as 1,500 pounds per acre. A general recommendation for corn and rice in Latin America is 100 to 150 of kg P_2O_5 per hectare for corn and from 0 to 60 kg for upland rice. In many cases, soils respond only slightly to phosphorus unless they are first limed (15). In an experiment, limed corn plots showed a marked response to 50 kg P_2O_5 per hectare with a yield increase from 0.8 to 3.2 tons per hectare. In limed plots, rice did not respond to phosphorus.

MANAGEMENT OF PHOSPHORUS FERTILIZER

Phosphorus responses are common in many tropical soils. Well-calibrated soil tests can identify the soils with a high probability of phosphorus response. Phosphorus management in soils with moderate fixation capacity is usually a simple procedure: small annual rates of superphosphate can be broadcast (spread over top of soil) and incorporated or banded (placed in a band near the seed).

In soils with high phosphorus fixation capacity, economically sound phosphorus management involves several approaches (56). Two general approaches are used to deal with high phosphorus fixing soils. One is to apply small to moderate amounts in bands near the plant. The other is to apply a large amount at one time saturating the soil's fixation capacity, eliminating the problem right away. However, this has

38-846 O - 85 - 9

a disadvantage because it requires a high initial investment and adequate financing. In a high-fixing soil from North Carolina, Kamprath (41) studied the residual effect of massive initial applications versus small annual maintenance rates applied in bands. In that study, the small annual banded application is superior to the massive single dose.

Applying phosphorus fertilizers in bands is a simple practice that satisfies the phosphorus fixation capacity of a small soil volume, making the fertilizer directly available to plants. In using a system of minimal inputs, banding is very appropriate since the goal is to increase crop production with minimal inputs without changing the inherent fertility of the entire soil volume. Sanchez (56) cites an example of banded versus broadcast applications in a high phosphorus-fixing soil in Brazil. The results showed that broadcast-incorporated applications were superior to banded applications in the first crop. Banded applications concentrated corn root development around the band. When a temporary drought struck, these plants suffered more than those of the broadcast plots because those had a more extensive root system. In time, however, the effectiveness of the banded treatments increased while the broadcast treatments decreased. Annually banded treatments began to approach the broadcast treatments as the phosphorus became mixed in the soil.

SOURCES OF PHOSPHORUS

Research in temperate regions indicates that phosphorus fertilizers should have at least 40 to 50 percent phosphorus in water-soluble form to ensure an adequate supply at early growth stages (23). Ordinary and triple superphosphate and monoammonium and diammonium phosphates meet this requirement and can be used effectively in soils with low to moderate fixation capacities.

In acid soils that fix large quantities of phosphorus, application of less soluble phosphorus sources such as rock phosphate may be more effective and economical than the slightly soluble forms. Rock phosphates are more reactive in acid soils and usually cost one-third to one-fifth as much as superphosphate per unit of phosphorus (56).

The literature on tropical agriculture is full of research indicating the desirability of high-quality rock phosphate sources over superphosphate in acid soils (46,4,23) and the poor performance of low-citrate-solubility rock phosphate sources in acid soils (3,50,66). Studies at TVA by Lehr and McClellan (45) indicate that when rock phosphate deposits (North Carolina and Tunisia) are given an index of 100, rock phosphates with a solubility index of 70 percent or greater can be recommended for direct application without testing. These are largely concentrated in North Africa, the Soviet Union, and the Southeastern United States.

The effects of rock phosphates of varying citrate solubility on flooded rice yields in an acid sulfate soil from Thailand was studied by Englestad, et al. (24). The initial and residual effects of the rock phosphates were highly dependent on their absolute citrate solubilities. The yield responses of the North Carolina and Florida rocks approximated those of triple superphosphate.

In the Tropics, high-citrate solubility deposits are limited to relatively small areas in Peru and India (56). The majority of the deposits in most tropical areas, including significant ones in Brazil, Colombia, Venezuela, Togo, and India have relative solubilities lower than 40 percent. Most are unsuitable for direct applications, but their reactivity can be increased by fine grinding or by thermal alteration and fusion with silica sand, sodium, or magnesium carbonates. These silicophosphates, called "Rhenenia" or thermophosphates, appear to have promise for acid soils that fix large quantities of phosphorus because of the blocking effect of silicon on phosphorus fixation sites (52,27).

The potential effectiveness of these cheaper forms of phosphorus in acid soils is illustrated in the following table:

Behavior of Different Fertilizer Sources on Wheat Grown in Oxisols of Southern Brazil

Phosphorus source	*Relative yield 5-year average*
No phosphorus	100
Olinda rock phosphate*	179
Simple superphosphate	206
Thermophosphate	218

*Low citrate solubility.

SOURCE: W. J. Goedert (personal communication) as cited by Sanchez (1976).

The low citrate solubility Olinda rock phosphate was inferior to ordinary superphosphate; but when thermally treated with silicates and carbonates to produce a thermophosphate, its effectiveness was superior to that of ordinary superphosphate. In view of the substantially lower costs of the rock phosphates and some thermophosphates, both seem desirable alternatives for soils with high fixation capacities.

An additional strategy, sometimes feasible for managing soils with high phosphorus fixation capacities, is to reduce their fixation through amendments that will block some of the fixing sites in the soil. This can be accomplished in some soils through liming or silicate additions (56).

Liming soils to pH 5.5 generally increases the availability of phosphorus by precipitating exchangeable aluminum and hydroxy aluminum. This has also been observed by Fox, et al. (29), in high fixing Hawaiian soils.

Applications of silicon or sand (an unessential element), usually as calcium silicate, sodium silicate, or basic slag, are known to decrease phosphorus fixation and increase phosphorus uptake by crops. In one study, grass yields increased from 2 to 7.6 tons per hectare and phosphorus uptake rose from 4 to 15 kg phosphorus per hectare when 1 ton of silicon per hectare was applied without added phosphorus (62).

Silicon is generally not considered to be essential to plant growth, however, positive yield responses have been achieved on highly leached soils of the Tropics under intense cultivation of sugarcane or rice. Soils having low contents of soluble silicon are most likely to show response to silicon applications. Fox, et al. (32), suggested that the critical level is 0.9 ppm silicon in water extracts. Responses have been obtained on the leached soils of Hawaii, Mauritius, and the rice soils in Japan, Korea, and Sri Lanka.

In these rice soils, silicon applications increased yields because of a more erect leaf habit, greater tolerance against insects and disease attacks, lower uptake of iron and manganese when present in toxic concentrations in the soil, and perhaps a rise in the oxidizing power of rice roots.

SULFUR DEFICIENCY

An element with plant requirements very similar to phosphorus is sulfur. Sulfur deficiency results in a reduction of growth and protein deficiency, often resembling nitrogen deficiency. Widespread sulfur deficiencies and responses have been reported all over the Tropics. McClung, et al. (48), observed sulfur responses in the Brazilian Cerrado in both savannas and recently cleared forests. In Central America, sulfur deficiencies are also widespread (51,28). Sulfur deficiency has also been found in sub-Saharan Africa and the sandy soils of central Africa (8). They have been reported in Asia (52) and in Australia and Hawaii (68,30). Sulfur-deficient soils are generally high in allophane or oxides, low in organic matter, and often sandy. Soils subject to repeated annual burning are often sulfur deficient since about 74 percent of the sulfur is volatilized (goes off as a gas) by fire. Sulfur-deficient soils occur in unpolluted, inland areas where the atmosphere is low in sulfur.

Sulfur requirements are similar to phosphorus in tropical conditions ranging from 0.1 to 0.3 percent of plant tissue. A sulfur deficiency at early growth stages may disappear later when the roots come in contact with the sulfur-bearing subsoil.

In general, small rates of sulfur (10 to 40 kg/ha) will overcome sulfur deficiencies. Sulfur as part of either nitrogen or phosphorus fertilizer is usually sufficient to take care of sulfur problems. If not, any soluble source containing sulfate will work.

POTASSIUM DEFICIENCY

The last major element to be considered, of less importance than the other nutrients considered here, is potassium. Potassium deficiencies do occur in the Tropics, however, lack of potassium is not nearly as widespread as nitrogen and phosphorus deficiencies. Boyer (10) in a review article suggests that the absolute minimum requirement of exchangeable potassium—the amount considered to be available to the plant—is close to 0.10 meq/100 g of soil but that this may vary between 0.07 and 0.20 meq/100 g depending on the kind of crops grown and the soils.

In Africa, the most severe potassium deficiency appears in the savanna on sandy soils. In the lower Ivory Coast, potassium application resulted in very substantial yield increase with oil palm (9). Potassium deficiencies have occurred in the southwestern Cameroon (64) in Madagascar (65) and in Brazil on sandy soils. Laudelot (45) in the Congo (Zaire) showed that the exchangeable potassium increased from 0.067 meq/100 g to 0.325 meq/100 after burning a forest. Thus, clearing a forest by burning substantially increases the potassium content of soils. Busch (12) found that the increases in bases (calcium, magnesium, and potassium) persists for a number of years after burning.

When soils are potassium deficient, fertilization with moderate amounts of potassium usually corrects the problem. High yield crops that contain high carbohydrates such as potatoes have a higher potassium requirement than a grain crop such as wheat or rice.

RICE

Since rice culture differs from other crops because it demands flooding, it must be considered separately. Regardless of their original pH values, most rice soils reach a pH of 6.5 to 7.2 within a month after flooding and remain at that level until dried (56). This increase in soil pH is a result of the release of OH. (base) ion when $Fe(OH)_3$ is reduced. Consequently, liming is of little value in flooded rice production. If low pH is a problem, flooding 2 to 3 weeks prior to transplanting may eliminate this danger.

Oxygen is consumed in flooded soils; therefore, nitrates will be lost via denitrification. Since ammonium is already reduced, it is stable in flooded environments. Organic matter decomposition proceeds at a slower rate without oxygen, however, materials such as rice straw (which has a high carbon to nitrogen ratio) may mineralize more rapidly under these anaerobic conditions, thus providing a source of plant-available nitrogen. Soil solution phosphorus increases upon flooding, explaining why additional phosphorus in flooded conditions is rarely needed.

Nitrogen use in rice is very critical. An ammonium source is generally used when fertilizer is used. It is incorporated in the soil before seeding or transplanting, or broadcast at different stages of growth. Incorporations of 2 inches are usually sufficient for constant flooding conditions. This places the nitrogen below the oxidized layer, a necessary condition to prevent denitrifiction (49). Nitrogen up-

take proceeds throughout the growth cycle of the rice plant but it is particularly critical during two physiological stages: at the beginning of tillering and at the panicle (grain head) initiation stage (47). Adequate nitrogen at tillering increases tillers, which is closely correlated with yield in short varieties. However, excessive nitrogen after maximum tillering and before panicle initiation may result in a large proportion of unproductive tillers and premature lodging in tall varieties. Excessive nitrogen after flowering may extend growth duration and increase susceptibility to some diseases.

The efficient use of nitrogen is very important economically. Scientists at the International Rice Research Institute (38) have almost doubled the efficiency of nitrogen fertilizer by either mixing it in mudballs or making urea briquettes. Fifty pounds of nitrogen per acre in this fashion was equal to 100 pounds per acre applied on the surface.

Rice rarely responds to phosphorus fertilizer except in highly weathered leached soils (57). Traditional soil tests for phosphorus do a poor job in predicting the need for phosphorus under flooded conditions.

Zinc deficiency is probably the most widespread micronutrient disorder in tropical rice, occurring in parts of India, Pakistan, the Philippines, and Colombia under low lowland conditions (63,69,15,39). It also occurs throughout the Cerrado of Brazil under upland conditions (19). In lowland rice, zinc deficiency is associated with calcareous (high base) soils and is accentuated by prolonged flooding. Deficiency can be corrected by applications of 5 to 15 kg of zinc per hectare as the sulfate or oxide incorporated into soil before seeding (35). An alternative is dipping the transplant seedlings in a 1 percent zinc oxide suspension before transplanting and mixing zinc oxide with pre-soaked rice seeds before direct seeding (69,15). Yield increase of 2 to 3 tons/ha have been achieved with 1 to 2 kg of zinc oxide per hectare (11). This again is an example of fertilizing the plant and not the soil, a much more economical and easy approach than treating the whole soil.

Potassium deficiency is rare in lowland rice as these soils are usually adequate in exchangeable potassium and receive potassium in the irrigation water when flooded. Soil tests are good for estimating potassium-deficient soils (56).

PLANTS THAT TOLERATE ADVERSE CONDITIONS

Up to this point this paper has concentrated on soil modification as a way to increase crop production. Another approach is to select or breed crops that will tolerate and produce well under natural, though sometimes hostile, conditions.

Certain crops grown exclusively in the Tropics normally grow at pH levels that would kill corn or soybeans (56). Pineapple is perhaps the best known example, but coffee, tea, rubber, and cassava also tolerate very high levels of exchangeable aluminum. Among the pasture species, several grasses and legumes are apparently very well adapted to acid soil conditions. Tropical grasses such as guinea grass, *Panicum maximum*; jaragua, *Hyparrhanea rufa*; molasses grass, *Melinia multiflora*, and several species of the genera *Paspalum* and *Brachiaria* grow well in very acid soils.

Legumes are considered very susceptible to soil acidity because of their high calcium requirements for nodulation. However, several tropical pasture legumes are strikingly well adapted to acid conditions. *Stylosanthes* spp., *Desmodium* spp., *Centrosema* spp., *Calopogonium* spp., and tropical Kudzu, *Pueraria phaseoloides* are the principal ones (56). Among the grain legumes, cowpeas and pigeon peas are more tolerant of acidity than field beans and soybeans. Many of these species have evolved in acid soils and have genetic properties that tolerate conditions associated with high aluminum levels.

On the basis of research, Spain, et al. (61), have produced a list of species adapted to high soil acidity and aluminum:

Crops and Pasture Species Suitable for Acid Soils With Minimum Lime Requirements

Lime requirement (tons/ha)	*Al saturation (percent)*	*pH*	*Crops (using tolerant varieties*
0.25 to 0.5	68 to 75	4.5 to 4.7	Upland rice, cassava, mango, cashew, citrus, pineapple, Stylosanthes, Desmodium, kudzu, Centrosema, molasses, grass, jaragua, Brichiaria decumbens, Paspalum plicatulum
0.5 to 1.0	45 to 58	4.7 to 5.0	Cowpeas, plantains
1.0 to 2.0	31 to 45	5.0 to 5.3	Corn, black beans

In a review of tolerance to aluminum, Foy (1974) concluded:

1. Some aluminum-tolerant varieties keep developing and are not injured.
2. Some aluminum-tolerant varieties increase the pH of growth medium which reduces the availability of aluminum; sensitive ones decrease soil pH, compounding the problem.
3. Some tolerant species accumulate aluminum in their roots or translocate (transport) aluminum at a slower rate to the top.
4. Aluminum in roots does not inhibit the uptake and translocation of calcium, magnesium, and potassium in tolerant varieties, whereas it does so in sensitive varieties.
5. High plant silicon is associated with aluminum tolerance in certain rice varieties.
6. Aluminum tolerant varieties do not inhibit phosphorus uptake and translocation as much as susceptible varieties or species. Also, many aluminum-tolerant species or varieties are very tolerant of low phosphorus levels.

Cassava Manihot spp., a tropical root crop growing widely on infertile soils that are frequently acid, has acquired the reputation for being a crop that yields well under very low fertility conditions (17). Cassava tolerates low soil pH and high levels of aluminum and manganese as well as low levels of soil calcium, nitrogen, and potassium better than many other species. While it has a high phosphorus requirement for maximum growth, it can use phosphorus sources that are relatively unavailable to other plants. It is highly tolerant of uncertain rainfall patterns and is an extremely efficient carbohydrate source on low fertility, acid soils with low levels of fertilizer applications. Cassava yields of 36 metric tons per hectare per year have been obtained under conditions that are suboptimal for many crops.

An estimated 1.57 million people live in the Tropics and this number is likely to expand to 5 billion in 50 years (55). This rapidly growing population will have to rely increasingly on plants as sources of both energy and protein. In the semiarid to subhumid climates, two-thirds of dietary calories come from cereals, while in the humid tropics the bulk of dietary carbohydrate comes from roots and tubers. The production of starchy root and tuber crops is inherently more efficient than the production of cereals, especially on marginal lands and/or land with minimal external inputs. It is estimated that with roots and tubers, at least two to three times more caloric energy can be produced per unit of land and time and with only one-third to one-half the production cost of cereals. It is, therefore, suggested that an increasing proportion of human energy needs will be derived from starch roots and tubers. The Tropics have a large amount of infertile lands, ill-suited for many crops with moderate to high nutrient requirements. One of the most serious problems of some tropical soils is phosphorus deficiency that seriously limits crop production.

Sweet potatoes (*Ipomoea batatas* (L.) Lam.), long associated with poor people and less productive soils, may be one solution (54). There is good reason that the sweet potato is grown so widely under such difficult conditions. Sweet potato had one of the lowest phosphorus requirements of the crops studied (Lettuce, *Lactuca sativa*; corn, *Zea mays*; and Chinese cabbage, *Brassica pekinesis*) (31).

The International Rice Research Institute (39), classified varieties of rice that are tolerant or sensitive to low phosphorus. They are

also selecting varieties for tolerance to iron deficiency or toxicity and the presence of toxic soil reduction products.

In summary, it is apparent that high production can be achieved on rather hostile soils as long as tolerant species or varieties of plants are selected. This would be a strategy that relies on no or minimal inputs and yet can increase food production substantially.

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Chapter XII

The Gene Revolution: Maximizing Yields in the Tropical Moist Forest Biome

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Contents

	Page
Abstract	227
Introduction	227
Economic Botany Laboratory	229
The Quest for Tolerant Germplasm	230
Intercropping	230
Legumes	231
Azolla as Fertilizer	232
Heat or Meat	233
Wood	233
Sewage	234
Oil Seeds	235
Allelopathy	236
Drug Crops	236
Essential Oil	237
Fiber Crops	237
Gums, Resins, and Balsams	237
Rubber	238
Wax Crops	238
Weeds	239
Tropical Moist Forest Biomass	239
References	242
Appendix A—Magic Mountain: 2000 AD	243

List of Tables

Table No.	*Page*
1. Estimates of Net Primary Production in Tropical Forests	240
2. Tropical Root Crops	240
3. Tropical Vegetables	240
4. Tropical Spices	241
5. Net Primary Productivity	241

Chapter XII

The Gene Revolution: Maximizing Yields in the Tropical Moist Forest Biome

It is the skills of plant geneticists, rather than large amounts of artificial additives such as pesticides and fertilizers, that have led to one record after another in crop yields in . . . both temperate and tropical zones (Norman Meyers, The Sinking Art, 1980).

ABSTRACT

Should there be a Gene Revolution, based on low-input multiuse extensive agroecosystems, to supplant the Green Revolution, based on high input intensive agriculture? Genes best adapted to the marginal environments found in the humid tropics should be pooled, combined, and recombined to produce moderate-yielding, well-adapted, multipurpose species. These gene combinations and recombinations should be tested, not for their yields in monocultural situations, but in well-planned, multitiered intercropped agroecosystems.

The search for appropriate genes can be scientifically directed by a computerized catalog of the varieties, cultivars, and species of potentially economic native and introduced species. Technologies that would be part of such a multiple-use agroecosystem would include small-scale biomass- and alcohol-fueled and solar plant-extraction equipment, as well as fermentation and distilling apparatus, designed to run on some of the products of the agroecosystem. In summary, the Gene Revolution should be directed toward a multitiered, multiuse, polygenic, low-input agroecosystem, fueled and fertilized from within. The Gene Revolution should pull together the five major ingredients important in marginal environments: 1) tolerant germplasm, 2) multiple and intercropping scenarios, 3) organic gardening (recycling animal and plant residues), 4) biological control of pests (including allelopathy), and 5) whole plant fractionation and utilization for such integrated agroecosystems. Such systems should be developed from existing farms, not from the forests.

INTRODUCTION

. . . Plant germplasm can be selected and superior cultivars developed on the basis of their adaptation to problem soils. Although we have moved slowly to capitalize on this information, it offers great promise in reducing energy inputs and improving the reliability of crop yields in both developed and developing countries (A. A. Hanson, 1976).

The highly weathered soils of the humid tropics will rarely support conventional crops for long periods without a high level of inputs. But such inputs are rarely affordable to developing tropical countries. If these countries cannot afford the inputs required for high-level production of conventional food crops, perhaps they should aim instead for a moderate production of nonconventional crops with moderate inputs. The Green Revolution, which called for maximum inputs, has pretty well run its course, maximizing productivity where high

inputs are possible. It is time for the Gene Revolution, to tailor existing plant types to maximize output with minimal input. The genes exist in nature, but they are disappearing fast. It is up to the Gene Revolutionists to get the genes together in the most meaningful manner, to maximize productivity under various low input scenarios.

With the end of the cheap energy era, developed and developing countries must reassess their imports and exports, their agricultural inputs and outputs, and their needs, often with a view toward substituting botanochemical fibers, fuels, and pharmaceuticals for those derived from petrochemicals.

Energy-hungry developing countries should closely watch developments at the Northern Regional Research Laboratory in Peoria, Illinois. If the botanochemical approach is practical today or tomorrow in an energy-rich country like the United States, then it will be all the more practical in the energy-poor countries of the humid tropics because:

1. Natural (and agricultural) productivity per unit area is higher in tropical than temperate zones, other things being equal. Hence, there should be much more biomass for a total-utilization scheme. The Gene Revolutionist is charged with finding the best genes and combining them in the best plants for maximizing output in the marginal low-input farm scenario.
2. The diversity of useful species on which to draw for our total-utilization concept is perhaps 10 times as high in the Tropics as in the temperate zone. Hence, the array of combinations for the recommended intercropping approach is staggeringly complex. The multitiered, intercropping agroecosystem being studied seems to be one of the most highly productive terrestrial agroecosystems, competing with the highly productive aquatic ecosystems of the Tropics. Yields of either of these systems can be improved vastly by the addition of ameliorated sewage sludge or other natural fertilizers in lieu of artificial fertilizer inputs. However, sewage sludge is recommended for biomass and chemurgic crops, *not* food crops.

In this talk, I will try to respond to the central issue: the highly weathered soils of the hot, wet tropics. These soils are rich in aluminum, silica, and iron, and poor in the common plant nutrients. What could USDA's Economic Botany Laboratory (EBL) do to improve "biological productivity of such soils without using much or any chemical fertilizer?" That is the charge put to me by the Office of Technology Assessment. Let's analyze that a bit before proceeding. Is it rare that we can improve natural biological productivity? Nature does a good job maximizing biological productivity under nature's constraints. If I compared productivity, I would only be comparing usable with total productivity. And if we are talking about the maximum Usability Concept, then we are not talking conventional agriculture at all.

Before laying out my plans for any country, I would analyze their import tables, especially the energy columns. Then I would plan a multitiered agroecosystem that would maximize benefits to the countries, import-export situation, seeking the best genes to maximize output for a modicum of inputs, under the ecological conditions prevailing. Geneticists could maximize the yields while American technology could maximize the extraction of useful products from the total yield.

Humid tropics has been variously defined. Most of my examples relate to what is called the Tropical Moist Forest (TMF), where annual biotemperatures are greater than 24° C and annual rainfall is between 2,000 and 4,000 mm. I have spent years in the Tropical Moist Forests of Latin America, and am still awed by the diversity of economic products endemic to the area. There are even more exogenous economic species from similar ecological zones outside Latin America. Unlike others in this workshop, I do not stress using native species, but I share the belief that we should not introduce exotics that are ill-adapted to an area. EBL's computer system helps find the right germplasm for a given tropical ecosystem.

Drawing on these tropical gene pools, the Gene Revoluntionist has perhaps more than 75 percent of the world's species to consider, perhaps 250,000 species. Each is a unique chemical factory, manufacturing biomass that we may need to draw upon as a source of energy. As the preface of the National Research Council's book, Conversion of Tropical Moist Forests, begins: "The tropical moist forest biome is biologically the richest, and least well known portion of the earth's surface."

Unfortunately, much of TMF is underlain by *ferralsols* (strongly weathered soils of tropical regions, consisting mainly of kaolinite, quartz, and hydrated oxides, and having a low base exchange capacity). Dudal (6) summarizes the mineral stress phenomena in such soils:

1. Deficiency in bases (Ca, Mg, K) and incapability to retain bases applied as fertilizers or amendments.
2. Presence (pH <5.2) of exchangeable Al, toxic to many species and active in binding phosphates.
3. Presence (acid soils) of free Mn, also toxic.
4. Fixation of phosphate
5. Deficiency of molybdenum, especially for legumes.
6. Fe and Mn toxicity shown by paddy rice.

Such soils are said to occupy more than a billion hectares, more than 8 percent of the world's soil.

There are those who say that conversion of TMF to agriculture will lead only to the so-called "red desert." Ewel (8) says, however:

> The red desert view of mature tropical ecosystem destruction is incorrect. Nature abhors a vacuum, so sites laid bare by human activity are quickly covered by some kind of community, although not usually the original one. We must face the fact that successional communities are going to be the dominant tropical ecosystems of the future.

ECONOMIC BOTANY LABORATORY

I am still awed by the diversity of the Tropical Moist Forest. Working at the Economic Botany Laboratory, I have begun to try to organize the information pertinent to the Tropical Moist Forest. There is already so much information that we depend on computers to assimilate the information. We are primarily concerned with the medicinal plants of the world, especially those with anticancer activity. Secondly, we are concerned with cataloging agronomic, ecological, geographical, and utilitarian information on economic plants of any description. From his studies alone, Schultes (23) compiled a list of more than 1,300 species employed by natives of the northwest Amazon as medicines, poisons, or narcotics. Our computer files already contain entries on more than 4,000 folk medicinal species, some of which double as food plants, fiber plants, dye plants, etc. We have yield data on some of these, under various ecological regimes in the Tropical Moist Forest.

With careful expansion, such a data base could catalog information on ecology, utility, and yields of all economic plants, and guide the Gene Revolutionists in their search for the right genes or germplasm. Details of some strategies that should be employed in the quest of tolerant germplasm are explored in Duke (7). Ecological data on more than 500 species suitable for exploitation in the Tropical Moist Forest are tabulated. I will not relate all those data here, but will present a few examples.

We know the conventional yield figures for only a fraction of tropical crops. Biomass or residue figures are even rarer, although such numbers are necessary for systems analysis of the yield potential of a multiuse agroecosystem. According to Westlake (29), conversion factors range from 1.3 to 4.0 for estimating aerial biomass from conventional yield units. I called all the experts I could find, in vain, in my search for the biomass figures for the temperate

lentil. Who would I call for such figures on the myriads of tropical products? The numbers do not exist. "The accuracy of productivity measurements is the lowest for tropical areas. The key to future refinement of our understanding the global productivity capacity lies, therefore, in the study of tropical primary productivity" (16). If biomass is a viable competitor in the energy field, it is time pertinent numbers were generated by baseline research program.

If I were Secretary of State, determining what strings were tied to AID funds overseas, I would see to it that funds went to carefully distributed research plots in developing countries. These plots would be funded to generate the numbers needed to support Maximum Utilization Concepts. How much biomass can we grow and harvest under various scenarios? Which scenario gives us the greatest net usable returns? I would fund no studies that did not give biomass yields related to climatic and edaphic data, and I would fund no country that did not make a commitment to preserve their current forests, and concentrate on increasing the productivity of current croplands.

Why should the remaining forests not be converted into agroecosystems? If they are lost, thousands of undescribed species will disappear forever before they have been named. Thousands of others will disappear with no studies of their economic potential. It is difficult to put a price on their heads. One in ten species studied shows anticancer activity; but only about 15 of the first 30,000 species studied in our anticancer program are of sufficient interest to have reached preclinical testing. Only one of those has resulted in thousands of remissions in cancer. This superstar, *Catharanthus roseus,* the Madagascar periwinkle, is a pantropical ornamental and folk medicine in Tropical Moist and Dry Forests. There are probably nine more superstars awaiting discovery (if they do not fall victim to the tropical axe). Can we afford to extinguish them?

THE QUEST FOR TOLERANT GERMPLASM

Elsewhere, I have advocated and outlined measures for seeking out the genes we need for marginal environments in the Tropics (7). Other research backs this idea:

> The correction of Al and Mn toxicities by liming is not always economically feasible, especially Al toxicity in strongly acid subsoils. However, plant species and varieties with species differ widely in their tolerance to both factors, and some of these differences are genetically controlled (10,25).

It is such differences we hope to capitalize on in the EBL Quest for Tolerant Germplasm. It is cheaper to increase yields by finding a cultivar that will tolerate the acidity, and its complications, than to increase the yields by importing 6 tons of lime per acre. This is just the first step in the Gene Revolution. Incorporating the appropriate genetically tailored species, varieties, races, and cultivars in a multitiered, multiple cropping system requires even further genetic selection, manipulation, and experimentation.

INTERCROPPING

Work on multitiered agroecosystems is proceeding most rapidly in Asia, but temperate systems are familiar to us all. Two-tiered systems, with hay, legume, or cereal crops alternating or intercropped with rows of fruit or nut trees, are common. Thousands of combinations are possible in a tropical three-tiered system. In one, pineapple was planted as the ground crop, cocoa as the first story, and pepper as the second story. Total harvestable crops and

residues from such systems usually exceed significantly the expected crops of the individual species, had they been planted in monoculture. Advocating agroecosystems that simulate the natural ecosystem it replaces Hart (12) says:

> The replacement of weeds by analogous crops and an increase in crop diversity will usually reduce the amount of energy used by weeds and pests.

Those systems of tropical forestry and agriculture that have been successfully employed for the longest periods are those that favor the maintenance of large mycorrhizal fungus population. Traditional shifting agriculture in small forest-enclosed plots probably attains mycorrhizal homeostasis. Mycorrhizae seem to minimize the expense to the host of seeking-out minerals. Cultivation of annual crops may lead to increased prominence of nonmycorrhizal species and grasses in weed communities. Soil sterilization can eliminate mycorrhizal fungi, and fungicides used against pathogens may adversely affect mycorrhizal fungi as well. Monocultures of crops that are probably nonmycorrhizal, such as grain amaranths and chenopods, might markedly lower mycorrhizal fungus populations and jeopardize subsequent mycotrophic crops (14).

LEGUMES

Even the nitrogen fixed by legumes is not free. Under conventional farming, there is a price to pay for the nitrogen contribution of the legume. In an unpublished paper, I pulled, at random, biomass yields for pure stands of C-4 grasses, C-3 grasses, and legumes. Though relatively higher in nitrogen and protein, the legumes yielded only half as much total biomass as the C-3 grasses, which in turn yielded only about half as much total biomass as the C-4 grasses. These are the biological costs (1) for nitrogen fixation and (2) excessive photorespiration. Although no one seems to have accepted my simple 1:2:4 ratio, I believe it. So called super-yield targets in the United States are 100 bushels of soybeans; the target for corn is 400 bushels.

Appropriate combinations of legumes and grasses seem to give the best yields for forage or hay, and probably for maximum utilizable biomass under renewable situations where water is not the limiting factor. The C-4 grass might give highest yields for a while, but it seems doubtful that such yields would be sustainable without the help of added N, be it from legume, crop residues, manure (green or brown), or sewage sludge. For high-quality leaf protein, the legume seems indispensable for most scenarios (without the sewage increment) whether the protein is for animal food, human food, or chemurgic use.

The amount of N fixed by legumes varies of course, but some of our economic legumes play a larger role than making beans and fixing nitrogen. According to Nigmator, et al. (1978), the cultivation of the legume licorice (*Glycyrrhiza glabra*) showed a marked ameliorative effect on saline soil in Uzbekistan, Russia. The licorice, in pure stands, did not form a complete soil cover during the first 1 to 2 years, but this was achieved by sowing it in mixture with sudan grass, cowpea, and lablab. The mixture decreased the evaporation and the rise of salts to the upper soil layers. Haines, et al. (11), reported that undersowing sycamore (*Platanus occidentalis*) with clovers and vetch in a discultivated, 2-year-old plantation suppressed weed growth to the point where height and volume increments of the young trees were increased significantly.

According to Felker (9):

> Leguminous trees have a unique advantage over annual legumes in dealing with the inhibitory effect of drought stress on nitrogen fixation because the deep-rooted leguminous trees may reach moisture, and thus relieve the plant of water stress for a longer time in the year than is possible with annuals.

An illustration of the ability of leguminous trees in semiarid climates to increase soil fertility more than annual legumes can be found

in West Africa, where yields of peanuts are increased if grown beneath Acacia albida trees.

The work on "teaching the grasses to fix nitrogen" goes on, but does not generate as many headlines as in the past. Nitrogen-fixation is being reported in more and more nonlegumes. Just this month, I noted an abstract dealing with nitrogen fixation in blackberries. Becking (2) assayed nitrogenase activity by acetylene reduction in detached *Rubus ellipticus* root nodules. It was similar to that in several nonlegume N_2 fixing nodules. The endophyte was an actinomycete.

AZOLLA AS FERTILIZER

While legumes are one source of fertilizer for our multitiered agroforestry units, tropical azollas might be another. Azolla, an aquatic fern, is a source of nitrogen. Clark (5), reviewing Azolla use in China, notes that Azolla "seed" are started in nurseries, then the seed ferns are introduced directly into rice paddies. In some areas, two rows of rice are planted with the Azolla growing in larger rows on either side of the double rice rows. Yields of 15 MT/ha of rice and 150 MT of Azolla have been reported for this simultaneous cultivation method. Rice grown with conventional fertilizers averages only 10 MT/ha (5). No mention is made of fish biomass harvested from such ecosystems. Could they also harvest 15 MT/ha catfish as have been reported from well-aerated Louisiana fishponds (21)? Grass carp (*Ctenopharyngodon idella*) and *Tilapia mossambica* are said to relish azolla, which has also been fed to cattle, chickens, ducks, and even has been suggested for human consumption. Typically, yields of grass carp are 10 times higher in the Tropics (1,500 kg/ha) than in the temperate zone (164 kg/ha).

Unfortunately, we do not know that Clark's 150 MT of Azolla is dry weight or wet weight; if dry weight, we have our fertilizer factory producing biomass equivalent to some of the highest reported, while increasing the yields of the rice crop, almost incredible. Here let me point out serious conflicts facing USDA officials: there are potent advocates and opponents of the introduction of many of the biomass wonders of the world (Acacia, Azolla, Leucaena, Prosopis, etc.) and the opponents hope that the advocates are willing to foot the bill should these wonders become the major weed of the 21st century.

I mention Azolla first because it is being championed as a free fertilizer, one producing 150 MT of biomass, while increasing the yield of rice by 1½ times. These are the "facts" hailed by the advocates. Azolla pinnata can double its biomass in 3 to 5 days, maybe 5 to 10 days in the field. Some claim that Azolla will suppress other weeds in rice, if not the rice itself. Other reports indicate the Azolla can either prevent mosquitoes from laying their eggs of their larvae from surfacing. Some say it releases nitrogen while alive, others only after death. Vietnam reports 1 MT/ha N fixed per year; China 0.7 to 1.8 MT N (13).

But there is a weed potential lurking there. Weeds cost the United States about $16 billion in 1979. Would Azolla introduce increase yields or would it clutter up more ponds than it helps. Responsible weed scientists as loudly and justly proclaim their fears as responsible forward-lookers champion this "free" fertilizer. There is no cut and dry answer.

On the negative side of the Azolla equation:

- In Japan, there have been complaints about Azolla covering the rice seedlings.
- In the Philippines, Azolla is called a weed in rice.
- In New Jersey, it has clogged up water channels to boat traffic.
- In South Africa, farmers claim it killed fish, prevented cattle from drinking the water, and clogged pipes.

HEAT OR MEAT

The Tropics may not face the heat or meat decision that temperate countries will face if there are no energy breakthroughs soon. According to some estimates, more than 90 percent of U.S. cereals and legumes are destined for animal food. If Americans went vegetarian tomorrow, and quit exporting grain, more than 95 percent of our agricultural biomass could go into ethanol production here. Some of us would rather be warm and do without meat, than be cold and eat meat regularly; others would say an emphatic "no." According to Meyers (19), much TMF biomass goes into cheap hamburger for the United States. Would it be better converted to fuel for the people of the TMF?

I have been a human guinea pig on three human nutrition studies at USDA, all involving high fiber and/or vegetarian diets. In one, 20 male subjects, none vegetarian or particularly sympathetic with vegetarianism, were fed soy protein in lieu of meat protein. None suffered from the soy as opposed to meat. On the contrary, there were no significant changes in the health of the subjects, at least by the standards investigated. From 40 to 50 percent of the human subjects preferred each soy analog to its meat counterpart.

Thanks to coal, America need not face the heat or meat crisis immediately. Thanks to the temperature of the humid tropics, the TMF might not face that choice either. But they might need to decide whether their biomass residues go into animal production or fuels for their machinery.

WOOD

Even today in the United States, wood is said to provide more energy than hydroelectric or nuclear power. Wood is a valuable byproduct of the multitiered agroecosystem, and the Gene Revolutionist should remember that in tailoring species for TMF.

> The growth rate of tropical weed trees characteristic of the humid lowlands are quite remarkable. I have measured naturally regenerated *Trema micrantha* in Costa Rica's OSA Peninsula, which were 9 m tall at one year, and more than 30 m tall at 8 years. It is these fast-growing, low-density trees which will constitute the wood resource of the future as mature tropical forests are felled and regenerate (8).

Ewel's figures for 13-month-old regrowth in various life zones are TWF, 12 MT/ha; TDF, 10 MT/ha; SWF, 6 MT/ha; SDFA, 5 MT/ha; and Tropical Montane Rain Forest, 1 MT/ha.

I do not advocate replacement of wood as a source of energy for cooking and heat in the TMF. I do advocate the production of cheap wood-burning devices for distribution to the poor. Most of the timbers of the Tropics go up in smoke, much of it wasted. With energy-conserving wood stoves, there would be more biomass available for the production and distillation of alcohol and other uses.

Liquid fuels for use in cars, trucks, and vehicles should be produced by all but the smallest farms in cheap mass-produced stills provided by the technologically well-off.

SEWAGE

There is justifiable concern that maximum use will strip the soils of organic matter. If we only use the above-ground biomass, we leave the below-ground biomass. According to Van Dyne, et al. (28):

> Below-ground production is more than twice above-ground in annual grasslands, but standing crops of biomass below-ground maybe five to ten times as much as above-ground standing crops.

The humid tropics do not lack water like the arid tropics, but they do need organic fertilizers, especially if continuously harvested. Here I take the opportunity to introduce into the tropical scenario an idea that I think should be exploited in the United States: piping sewage sludge out of the cities of the world and into energy farm areas. The pipeline routes could parallel proposed coal-slurry lines, natural gaslines, or petroleum pipelines. Oil shale mines, strip mines, any type of old mine site could be partially or totally reclaimed or improved with sludge-planted areas. The highest biomass yield reports I find are from The Wealth of India, where such yields as 160 MT/ha for *Pennisetum purpureum* are reported for fields irrigated with sewage. Westlake (29) reports unusually high yields even in the temperate zone. With sewage irrigation and intercropping, he reported DM yields of mixed alfalfa-orchardgrass at 26 to 39 MT/ha, at least five times greater than the expected yield of alfalfa alone, without sewage irrigation. This compares with 40 MT for *Phragmites australis*, which Westlake describes as the most productive temperate community.

City planners should adopt the Design With Nature Concept, building above the productive alluvial plains, clearly the most productive lands in any biome, with nothing but natural inputs. Alluvial plains and energy sumps should occupy the fertile lowlands, while no more building on the floodplains should be permitted. These most fertile lands are being gobbled-up by suburban creep, here and elsewhere.

I decry the cancellation of plans to barge sludge to Haiti, because I believe sewage sludge could play a big role in the greening of Haiti or the Sonoran or Negev deserts for that matter. We could concomitantly alleviate the shortage of water and organic matter in the desert, with its low real-estate values, while alleviating the waste disposal problem in the cities, with their high real-estate values.

Water-borne sludge could prove a boon to the humid tropics. If sewage sludge can double yields in the humid tropics, the reverse pipeline could be shipping ethanol out, still leaving a positive balance in organic matter in the humid tropics. Once the pipelines were established, the sludge could be a free input, doubling outputs. Hence, I see this untried concept as one way to double the productivity of the humid tropics, or treble the productivity of the arid tropics, with a free input. The excess yields could be devoted to production of alcohol, for internal or external energy use.

Such an area might appropriately be called an energy sump, and would not be an attractive place to live, but the products of the energy sump could make jobs there, and a higher standard of living elsewhere.

Here, as much as anywhere, the talents of the Gene Revolutionists will be called into play. The genes for maximizing productivity in the energy sump will be very different from those for maximizing productivity in the unaltered humid tropics. Planting, cultivating, weeding, and harvesting technologies, even the recommended varieties, if not species, will be different for the two scenarios.

OIL SEEDS

Back in April 1977, I suggested that palm oil might someday be competitive with petroleum. Today, foreign palm oil in New York is still higher than domestic petroleum at the pump, but at the rate the gap has closed since my paper. Palm oil will be as cheap as petroleum by the year 2000.

Oil palm is one of many species with varieties tolerant of the allic soils of the humid tropics. Oil palm is currently growing in countries that show deficits in both edible oils and energy. It has already been shown that simply growing legumes between the oils palms can increase oil yields by 2 MT/ha/yr (3) or the equivalent of 6 barrels of oil per hectare, simply by the selection of proper legume for intercropping. These legumes (*Centrosema pubescens, Pueraria phaseoloides*), in addition to increasing our energy budget, at little or no cost following planting, can provide food, conventional or unconventional. I am sure, based on temperate figures, that more protein per hectare will be produced if the whole aerial biomass of the legume is harvested, thrown into our energy vat, the leaf protein extracted for human consumption, the carbohydrates for ethanol production, the residues for return to the soil.

We have spoken only of the oil yields of the oil palm. There is still a lot of unused biomass, which could go, depending on the outcomes of our systems analysis, into ethanol production, internal or external combustion devices and/or soil amendments.

Not all, but most palms, survive or thrive in the humid tropics. Like the oil palm, they are multiple-use plants, prime candidates for the upper or intermediate stories in the multitiered agroecosystem for the humid tropics. Could we not multiply the yields of these unstudied palms by 10 as we have done with the Hevea rubber plant. Let's look briefly at one mentioned by Amazonian expert R. E. Shultes (23):

> *Orbignya martiana*: One palm may produce a ton of nuts a year, 198 pounds of which is kernel . . . with up to 72 percent of an almost colorless oil very similar in composition to coconut oil. The seed cake remaining, containing 27 percent protein, is an excellent animal feed. I read this as a ton of biomass per year, more than 100 pounds of which is oil. I don't know that these figures are more or less reliable than those with which Calvin derived 50 barrels of diesel per acre. Conservatively, it would take four of these productive palms to produce one barrel of oil per year, or 200 trees to produce 50 barrels. From my experience in Latin America, I would pin my 50 barrels/acre hope on the palm before I would Calvin's Diesel Tree. Calvin figured at least 100 trees per acre, but his trees were 1 m in diameter. I don't know any palms that big. Thin canopied palms would permit intercropping of food crops, which I speculate would be impossible in the shade of "diesel trees."

Note that with our hypothetical *Orbignya*, with no genetic research, we are getting 50 barrels of palm oil per acre, with a residue of 1,900 pounds per tree. We have assumed a tree producing 2,000 pounds of fruit, 100 pounds of which is oil (3,300 pounds are reported, with an oil yield in excess of 200 pounds oil per tree). Assume 300 to 350 pounds per barrel of oil. We can further assume after the extraction of our 100 pounds of oil, we have 1,900 pounds of biomass in the pot, 900 pounds of which might, conservatively, be water. Of the remaining 1,000 pounds, perhaps there is another 100 pounds of protein, per tree, and 900 pounds of carbohydrates, etc., 400 pounds of which might give us another barrel of ethanol per hectare. So, hypothetically we have 100 pounds of protein and 2 barrels of ethanol as byproduct from our 1 barrel of palm oil.

The technology needed for this oil palm scenario:

1. oil extraction (available for oil palm);
2. carbohydrate fermentation and distillation; and
3. protein purification and sanitation, for human or animal production.

There are palms for the arid tropics, for the humid tropics, for brackish swamps, for fresh-

water swamp situations, and for our sewage sump, all potentially intercroppable with other food/energy/chemurgic crops. But the Gene Revolutionist has not started to tailor these species to specific environments and to increase their yields. And we have not even talked about the waxes, steroids, leaf-proteins, and ethanol that could be produced by the leaves. Some palms will disappear before we have studied their potential.

Production of conventional palm oil (from Elaeis) was expected to total 4.3 million MT in 1979-80, compared to 3.9 million MT in 1978-79 (1). Whether or not these are viewed as petroleum alternatives, many oilseeds are handled in the U.S. market. Residues could be used for alcohol or methane generation, or as a soil amendment.

Some prices quoted in the Chemical Marketing Reporter for various tropical oilseeds during 1979 are avocado ($3.13/lb), castor oil ($0.40/lb), coconut ($0.57/lb), corn ($0.50/lb), cottonseed ($0.18/lb), oiticica ($0.60/lb), palm ($0.33/ lb), palm kernel ($0.42.lb), and soybean ($0.48/lb). The newly generated market for jojoba "oil" has a cult of followers, but this so-called oil is a liquid wax, unique to the jojoba among plants. Soy oil, peanut oil, and sunflower oil have been used as diesel substitutes.

ALLELOPATHY

Allelopathy has not yet been developed to be an alternative to herbicides. But if different chemurgic species are selectively herbicidal, as one gathers from reading the allelopathic literature, then all these herbicidal activities should be cataloged. Residues of the allelopathic species might then be returned to the intercropped agroecosystem where its herbicidal effects will do the most good and least harm. One can even suggest how coumarin-containing residues (Melilotus, Trigonella, etc.) can be used to stimulate rooting in the softwood cuttings used for propagation in our tropical agroecosystem (17). Steenhagen and Zimdahl (26) show that the hydrocarbon-producing *Euphorbia esula* reduces the frequency of quackgrass and ragweed, but also reduces the growth of tomato seedlings. Dry leaves of the medicinal species, *Parthenium hysterophorus*, inhibit growth and nodulation in legumes, branching in tomato and plant height in ragi (*Eleusine coracana*) and reduce the yield of bean, tomato, and ragi. On the other hand, the leaves stimulate the growth of *Pennisetum americanum* (15). Such data are being generated rapidly, but there seems to be no computerized catalog to enable us to evaluate and use these data effectively in planning multiuse agroecosystems.

DRUG CROPS

The Economic Botany Laboratory specializes in medicinal plants. We have found that there are often huge residues of biomass following drug extraction. It takes 1½ MT of dry stem and bark of Maytenus to yield a gram of maytansine, one of the anticancer superstars of the last decade.

Bruceine, cassia, caffeine, cocaine, heliotropin, ipecac, papain, pilocarpine, quinine, quinidine, reserpine, rutin, steroids, and theophylline: these are a few drugs that can be harvested in the humid tropics. Many of these are million dollar items that could be extracted on-site as income producers, leaving behind 99 percent of the biomass for food and/or fuel production. Some drugs might be byproducts from conventional foods, e.g., caffeine from coffee and tea, theophylline from tea, steroids from legumes, rutin from buckwheats. The steroids once derived from tropical dioscoreas ("barbasco") are now largely derived as byproducts of legumes and agaves.

ESSENTIAL OIL

The United States imports nearly 10,000 MT of essential oils at close to $100 million per year. This probably represents the distillation of about one million MT of biomass, 99 percent of which could have been funnelled into food and fuel production as byproducts. By no means all of these essential oils are humid tropical species, but I list a few that are from the humid tropics:

- *Trees*: bay, bergamot, camphor, cassia, cinnamon, clove, copaiba, grapefruit, guaiac, lemon, lime, linaloe, nutmeg, petitgrain, ylang-ylang
- *Forbs*: cardamon, citronella, ginger, lemongrass, palmarosa, patchouli, vetiver.

The trees might be considered as alternating trees or strata with other trees, like palms, in the upper strata of our multitiered agroecosystem. The forbs might be considered for the ground layer. Our Gene Revolutionists should already be looking for tolerance to shade and root competition in our lower tier, and tolerance to root competition in candidates for the upper tier.

FIBER CROPS

On the last day of October 1980, an official called from the Strategic Materials Department to ask where in our 50 States we could grow several strategic materials. Among them were two tropical fibers, abaca and sisal, the former adapted more to the humid tropics, the latter more to the arid tropics. With sisal, fiber yields are only 3 percent of the leaves. From the remaining 97 percent biomass, I am certain that steriods, waxes, leaf protein and alcohol, even tequila, could be produced. Many natural fibers can be produced in the humid tropics, among them abaca, baobob, coir, cotton, ensete, hemp, henequen, jute, kenaf, remaie, roselle, sisal, snakeplant, sunn hemp, etc. As the cost of petrochemicals rise, some economists predict a return to natural fibers instead of synthetics.

GUMS, RESINS, AND BALMS

Some chemicals in this group approach the classical petrochemical or "neoclassical" botanochemicals. Swedish and Finnish firms are reported to have developed an efficient turpentine car engine that runs on turpentine produced from the oleoresin of scotch pine. High road mileage is claimed for turpentine (20). Presumably, yields of tropical pines may be higher than the temperate pines. The Gene Revolutionist would be charged with increasing both the nut (pinyon) and turpentine for specified intercropping stratagems under specified ecological conditions.

Copaiba oil, traded at over $2.00 per kilo, may or may not be the same as the oil from Melvin Calvin's tropical "diesel tree" *Copaifera langsdorfii*. According to Dr. Calvin, (4) 1½ inch holes drilled halfway through large trees about 2 feet above the ground yield about 20 liters of "diesel" (mostly 2 or 3 main C-15 sesquiterpenes and 30 or 40 minor C-15 sesquiterpenes) in two hours. The holes are bunged and retapped again in about 6 months, and said to yield another 20 liters of diesel, or 40 liters of diesel per year per tree. This is exactly the same yield reported in Grieve's *Modern Herbal*, 1931. Dr. Calvin, perhaps optimistically, calculates that we can get 25 barrels of diesel per acre per year on a sustainable basis from the copaiba tree (18). Unfortunately, the tree seems to be intolerant of frost. I will be getting resin from an equally productive timber species of *Copaifera* during my next trip to Panama.

Gum arabic, guar, karaya, locust, myrrh, olibanum, and tragacanth are among some of the vegetable gums now traded. With problems in Iran, a major producer of tragacanth, prices of tragacanth have risen considerably. In April 1979, 56,900 pounds of tragacanth were imported with a value of $608,346. More than 23 million pounds of guar gum were imported in that same month. Acacia, Tamarindus, and Sterculia are major tropical sources of gums that can provide renewable harvests in intercropping strategies.

RUBBER

The first *Hevea* plantation set out in the Far East yielded about 450 pounds dry rubber per acre, while currently available clones yield about 3,000 lbs/acre (< 10 barrels). New chemical treatments applicable during tapping can increase the figure to 6,000 lbs an improvement of 13.3 times. These yields are available while leaving the biomass intact. Other options might be to grow whole plants for rubber extraction between our upper story palms in the humid tropics. The Petroleum Plant from which Calvin once projected 50 barrels per acre could be grown in the humid tropics as well as the arid tropics. Detractors from Calvin say yields would be closer to two barrels than 50 barrels from the "Petroleum Plant."

Calvin's plant has received other headlines under the name of gopherweed (*Euphorbia lathyris*):

> Melvin Calvin, Nobel Laureate in Chemistry, believes that the U.S. could produce more than 2 million barrels a day of gopheroil by 1995. The Department of Energy has granted Calvin $250,000 to continue his research. Marvin Bagby, head of the Agriculture Departments hydrocarbon-plant research project, thinks that gopherweed is the leader among 45 hydrocarbon-bearing plants that have commercial promise (1).

Other species of Euphorbiaceae are better adapted to and more productive in TMF than the headliners Calvin promoted. The latex of milkweeds could more appropriately be funnelled into rubber production. Be it spurge or milkweed as hydrocarbon sources, the whole plant would be thrown into the extraction vat, with waxes, drugs, rubber, leaf-protein and ethanol as feasible byproducts, all grown between our upper-story palm trees. Whether Calvin gets 2, 10, 25, or 50 barrels/acre of petroleum or rubber from the "petroleum plant," gopherweed," or "diesel plants," I maintain that the ethanol potential from the residues has more energy content than what he obtains.

WAX CROPS

Waxes tend to be more frequently derived from arid land plants than humid tropical species. But if the wax can be taken as byproduct, like ethanol, following extraction of edible leaf protein, humid tropical waxes might become export money-makers. In the Chemical Marketing Report, one finds such waxes as the temperate bayberry wax ($3.00/kg), the arid lands candelilla wax ($3.00/kg), and the subtropical carnauba wax ($4.00/kg). Yields rarely exceed 1 percent of the plant, leaving 99 percent of the biomass as waste, or better as leaf-protein or energy stock. One second-growth "weed," *Calathea lutea*, of the humid tropics, could serve as source for food, wax, and biomass, as could members of the banana family. The Calathea is easily propagated with as many as 30,000 plants per hectare, yielding up to 70 pounds of wax per acre (23). I project that would leave at least 29,700 pounds dry weight of biomass in the vat for leaf protein and ethanol production. This leaves the underground roots untapped. Aerial biomass yields of 18 MT/ha might complement the edible-

rooted *Calathea allouia* (12 MT root/ha). Here we must remember that increases in the below-ground yields will usually be compensated for by losses in above-ground yields. Calathea and other tropical plants, now all but unexploited, can yield food, fiber, fuel, and residue for the energy farm of the humid tropics.

WEEDS

Neither the Weed Science Society of America (WSSA) nor the oil companies have loudly advocated the use of biomass as an energy alternative in the past. I find it interesting that there were five items in the October 1980 Newsletter of the WSSA hinting at plants as a source of energy. Not necessarily believing the figures myself, I summarize the estimates from that WSSA newsletter:

- *Euphorbia*: 50-125 bbls/ha.
- *Salsola*: Arizona grant to make fuel from the Russian thistle, a serious weed.
- *Asclepias*: Improved variety of milkweed could be source of biomass for synthetic fuels and chemical feedstocks and a source of fat, protein, oil and fiber. Lab estimate of 60 bbls/ha crude oil.
- *Parthenium*: Guayule provides a latex that can be used for fuel, petrochemicals, and rubbers.
- *Simmondsia*: Speculation holds that mature jojobas might produce the equivalent of 50 bbls/ha.

It might be added that these optimistic estimates are based on marginal weed species in areas of marginal inputs. But these are gross energy outputs. Whether it would take 100 to 250 bbls/ha input to obtain the 50 to 125 bbls/ha output is speculative. No one has analyzed the energy inputs required to obtain these optimistic outputs. Research should provide these numbers.

A more pessimistic note comes from Shell's "Ecolibrium" 9(4):1980:

> According to the Gold Kist plant officials, a good peanut crop can reap 142 gallons an acre. And, unlike alcohol from grain, you don't have to distill peanuts to get oil, you just squeeze them. The peanut oil costs about $3.00 a gallon.

The 142 gallons an acre is equivalent to less than 10 barrels per hectare.

This shows the wide disparity in figures used by optimists and pessimists. Scientific research should rectify this disparity.

It seems doubtful that the herbicide industry would encourage hand harvesting of weeds and their conversion into alcohol and/or protein. I advocate just that in TMF countries with unemployed hungry people. Almost all studies show that hand weeding, though using human labor, results in better yields than herbicide controls. In some cultivated communities, weeds constitute 8 to 27 percent of the shoot biomass. This 25 percent might represent 2.5 MT on a tropical hectare, which could be harvested and converted to fuel, at the same time increasing the yield of the crops the weeds were competing with.

TROPICAL MOIST FOREST BIOMASS

Do energy farms produce more biomass than the pristine moist forest produces? Those who speak of highly productive TMF mention great quantities of biomass. The climax forest is in equilibrium, metabolizing as much as it synthesizes, so that although gross production may be extremely high, metabolism erases the profit, leaving no net biomass increase. Do agroecosystems produce more total biomass than native forest ecosystems? I cannot say categorically. The optimist figures on arid land weeds yielding 50 to 125 barrels of oil per hec-

tare; the pessimist peanut prospectus lies at less than 10 barrels per hectare. And we see estimates of up to 150 MT dry weight from some tropical grasses under sewage irrigation. These figures suggest to net that agroforestry is more productive of biomass than the climax forest. Estimates of the net primary production of tropical forests (table 1) presented by UNESCO (27) range from 9 to 32.

For comparison, I list in tables 2 through 4 some examples of yields of tropical crops that can be grown in the lands occupied by the forests mentioned in table 1. These data, gathered from a variety of sources, do not consistently represent maximums, minimums, or means, nor are such data available. Hence, these numbers cannot be compared.

Today the biomass data bank at the Economic Botany Laboratory has close to a thousand entries in it. EBL is probably the best equipped lab in the USDA to compare biomass potential of different moncultural, polycultural, and natural ecosystems. Consequently, I have brought my computer to this workshop so you can check it out on the spot. Incidentally, EBL is probably the best equipped lab in the USDA to give you the ecological amplitudes, nutritional analyses, and folk-medicinal attributes of the little known economic plants of TMF, some of which now extant, may soon be extinct.

Table 2.—Tropical Root Crops (yields in MT/ha)

Arrowroot	37
Canna	85
Cassava	56
Gallan	120
Ginger	30
Groundnut (bambarra)	4
Leren	12
Lotus	5
Peanut	5
Sweet Potato	36
Taro	128
Turmeric	35
Yambean	90
Yautia	32

Table 3.—Tropical Vegetables (yields in MT/ha)

Banana	18 MT
Cantaloupe	14 MT
Eggplant	24 MT
Garlic	10 MT
Okra	23 MT
Onion	29 MT
Pepper	14 MT
Pigeonpea	13 MT
Plantain	45 MT
Pumpkin	23 MT
Squash	23 MT
Tomato	22 MT
Tomatillo	36 MT
Yardlong bean	10 MT
Watermelon	20 MT

Table 1.—Estimates of Net Primary Production (MT/ha/yr) in Tropical Forests (UNESCO, 1978)

Forest type	Location	Net production
Equatorial	Yangambi, Zaire	32
Equatorial	Khao Chong, Thailand	29
Secondary forest 40 years old	Kade, Chana	24
Lowland dipterocarp	Pasoh, Malaysia	22
Bamboo in monsoon forest	Burma	20[a]
Subequatorial (Banco plateau)	Ivory Coast	17
Bamboo in rain forest	Burma	16[a]
Dry deciduous	Varanasi, India	16
Lower montane	El Verde, Puerto Rico	16
Subequatorial (Yapo plateau)	Ivory Coast	15
Seasonal rain	Anguededou, coastal Ivory Coast	13
Mangrove	Puerto Rico	9

[a]Estimate does not include roots.

Table 4.—Tropical Spices

Trees:		
Allspice	Pimenta dioica	
Bayrum tree	Pimenta racemosa	
Camphor	Cinnamomum camphora	
Cassia	Cinnamonmum aromaticum	
Cinnamon	Cinnamomum verum	
Mace	Myristica fragrans	
Herbs and vines:		
Lemongrass:	Cymbopogon citratus	95 MT WM
Patchouli	Pogostemon cablin	36 MT WM
Pepper, black	Piper nigrum	6 MT (fr)
Vanilla	Vanilla fragrans	1 MT (sd)
Vetiver	Vetiveria zizaniodes	2.5 MT (rt)

Table 5 presents estimates of standing phytomass and net primary productivity for some of the various vegetation types that might be expected in a tropical country. I believe, but cannot prove, that intensively managed agroecosystems used in places formerly occupied by these forest types could produce two to five times as much (except for the alluvial swamp forests). I do not advocate replacement of forest with agroecosystem, but better management of existing agroecosystems.

Table 5.—Net Primary Productivity

	Republic of Panama Phytomass MT/ha	NPP MT/ha
Tropical:	240	18
Humid tropics:	440	29
Bright Ferrallitic Evergreen	650	27
Swamp Forest	500	25
Bogs	300	150
Monsoon Forest (Savanna) Red	200	16
Monsoon (Dark Soil)	80	15
Alluvial Forests	250	70
Mangrove	130	10
Submontane Evergreen	700	35
Submontane Monsoon	450	29
Semiarid tropics:	107	14
Xerophytic Forest (Ferrallitic)	250	17
Grass Shrub Savanna (Redbrown)	40	12
Grass Shrub Savanna (Black)	30	11
Grass Shrub Savanna (Solonets)	20	7
Swamp Savanna	60	14
Alluvial Gallery	200	60
Sub montane Xerophytic Forest	200	15
Sub montane Savanna	40	12
Arid tropics:	7	2
Savanna (red-brown soils)	15	4
Alluvial Gallery	150	40
Tropical Desert	1.5	1
Psammonphyte on sand	1.0	0.1
Desert (Coalessed soil)	1.0	0.2
Halophytes (solanchaks)	1.0	0.1
Submontane Desert	7.0	2.0
Subtropical:	133	14
Humid subtropical:	366	25
Bright ferrallitic Evergreen	450	20
Rendaina Evergreen	380	16
Prairie	30	13
Swamp Forest	400	22
Meadow Bog	200	130
Gallery Forest	250	40
Submontane Forest	410	18
Semiarid subtropics:	99	14
Xerophytic Forests	170	16
Shrub-steppe (Gray-Brown soil)	35	10
Shrub-steppe (Soloneta)	20	6
Shrub-steppe (Chernoaenoid)	25	8
Psammophyte on sand	20	5
Halophytes on Glanchak	1.5	0.5
Gallery Forest	250	40
Submontane Forest	120	13
Submontane Shrub-steppe	99	14
Arid Subtropics:	14	7
Steppe desert (Serozem)	12	10
Desert (sub-desert soil)	2	1
Psammonphytes on sand	3	0.1
Desert on takyrs	1	0.5
Halophyte on solonchak	1	0.2
Gallery Forest	200	90
Submontane Desert (Serozem)	15	12
Submontane Desert (Desert soil)	3	1

SOURCE: Rodin and Brazil in Lieth, 1978.

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APPENDIX A—MAGIC MOUNTAIN: 2000 AD

by James A. Duke[1]

Twas the year 2000 on Magic Mountain, in the Tropical Moist Forest Life Zone. None of the natives lived by the river anymore. After the last flood they abandoned the last alluvial homesite and moved up on top of Old Magic. This freed 100 of their most productive hectares for agriculture. Untended slopes yield 30 MT/ha biomass each year and the ridges where they now have their residences yield only 15. The bottomland they abandoned, fertilized by the floods that used to destroy their homes periodically, yields 150 MT/ha. With the help of leaf-protein extraction equipment, they are getting 3 MT protein per bottomland hectare, but the bulk of their bottomland biomass goes into barrels, as ethanol. Lo and behold, they are getting 2 barrels of alcohol for every MT of biomass, using firewood and residues to fuel the distillation, applying the ashes back to the farm. That's big money these days with ethanol at $100 a barrel, oil at $200. Instead of sending them arms, powdered milk, peanut butter, and fertilizer, the United States sent them LP (leaf protein) extractors, seeds (computer-selected for this ecosystem), inoculum, stills, and energy-producing portajohns.

Back in the 1990s some of the donors from the overdeveloped countries realized that they could nitrogenate more acres in the tropical backwoods with a kilo of inoculated legume seed than a kilo of nitrogen. Adventist Missionaries made their point back in 1990 when they showed the natives that they could get 10 to 20 times as much protein from leaves if they did the conversion themselves rather than let the cattle do it. So now, each hectare gives 3 tons of protein instead of 300 kg. As a byproduct they have 100 barrels of ethanol, worth $10,000. With their tropical climate, conducive to higher productivity, they are now exporting ethanol to the United States at $100 a barrel, while the Arabs are having trouble finding buyers for their oil at $200 a barrel. Instead of bananas at 5¢ a finger or coffee at one clam per kilo, the barge that chugs up the river hauls ethanol out for those profligate spenders up in the United States who are still sitting on their coal, to give them the energetic upper hand in case the Russians don't get out of Poland, Afghanistan, Syria, and Iran (all of whose oil had been burned up by saboteurs).

Neophytes to the Tropics thought that Magic Mountain was Virgin Rain Forest, but those of us in the know knew that nearly all of Magic Mountain was a multitiered, multiuse agroecosystem. The Virgin Rain Forest was the next ridge over, by Rocky Rapid River, i.e., Meyers Mountain. Rocky Rapid River still provides cold clear water and the electricity consumed on Magic Mountain. Meyers Mountain, now a State Park, has several endemic species that are being studied by the Natural Products people looking for better contraceptives and cancer cures. Neophytes thought this was Virgin Forest because it had more than 100 tree species per hectare in at least two tiers. Palms and legumes stuck out on top, with coffee and cacao in the lower tiers of some, leguminous vines in others, lemongrass in others, yams in others, and zingiberacous spices in the shade of others.

Finding forest on magic mountain surprised a lot of armchair botanists, who, back in the 1980s predicted that the forest would be reduced to savannoid "red desert." But there were at least three strikes against the "red desert" hypothesis: 1) the Secretary of State convinced the President that trees alleviated rather than aggravated the pollution problem, so Americans were not running a "Down With Trees" campaign, 2) natives had experienced fewer bug and disease problems in their multitiered agroecosystems than in their brief monocultural experiments, and 3) Americans had encouraged a forest "barrier" between the hoof-and-mouth disease of Colombia and the Hamburger Farms in Central America. The Neophytes thought that the Americans had taught the Indians this multitiered approach, but, in fact, the Indians had taught the Americans. Even in temperate America, the Indians were intercropping when Columbus got here, with beans fixing a little nitrogen to supplement that left by the decaying fish they placed with their C-4 corn seed. The C-3 pumpkins we used for our Thanksgiving pie were used by the Indians as well. But they knew that the cucurbits smothered weeds long before young Dr. Duke discovered that cucurbits not only smothered the weeds, but allelochemically discouraged them.

The standard of living was almost as high on Magic Mountain as it was in New York City. A few hippies and naturalists thought it was even better. It seems that in spite of marvelous inventions in solar energy and energy conservation (halving the consumption of individual appliances), the Amer-

[1]This is a fictional presentation created by Jim Duke for the Office of Technology Assessment. It reflects the personal opinions of the author.

icans were still energy guzzlers. They now had electric nail clippers, electric combs, and electric toothpicks, and they had to recharge their electric cars in offpeak hours with their palm oil and ethanol-fueled generators. These were located on offshore barges for the receipt of the barrels of ethanol and palm oil flowing in from the neotropics. The gringo still heats his home 6 months of the year to 72° F and cools it 6 months of the year to 62° F, wearing short sleeves in the wintertime around the house and coat and tie during his air-conditioned summer. Jim Duke said you could fuel America with sewage-irrigated biomass (if Americans went vegetarian) and Melvin Calvin said Arizona planted to the petroleum plant (*Euphorbia lathyris*) could satisfy the energy needs of the United States. Szego and Kemp said you could do it with Btu bushes. But America went on and paved its bottomlands, its most productive farmland, which now sells at $200,000 per hectare. No one really knew who was right. Should they have believed Vergara and Pimentel who said that all the biomass in the United States would support only 2½ percent of their energy needs (while in 1980 concluded that biomass already supplied 2 percent of U.S. energy consumption and could supply up to 20 percent by 2000), or estimates of 10 percent (like Dugas came up within California), or those who said U.S. consumption about equals the net annual storage of solar energy in U.S. biomass, or Vietmeyer who accepts Calvin's suggestion that Arizona planted with petroleum plants could fuel all the United States?

There aren't too many animals on Magic Mountain and these are there more for biocontrol than for meat. Sam Swindell has a bunch of pigs that are rotated from one alluvial farm to another when the nutgrass gets out of control. Seems that the nutgrass was evolving just as fast as the herbicides. The last generation of nutgrass herbicides reduced yields of the crop by 50 percent. One group of hippies down in Guyana had started making a beverage (Chufa Cola) out of the nutgrass tubers, using the aerial biomass to generate the energy to run their operation. But nutgrass got so rare that Chufa Cola is barely competitive with Coca Cola anymore. Tommy Tucker intercrops turkeys with the legumes in his orchards, largely to control weeds as suggested by Surguladze. Joe Groats has a few goats he stakes out whenever the tropical Rubus the gringos introduced for nitrogen fixation gets out of hand.

The Rice-Azolla farmers let the geese help the Azolla keep down the other weeds, while the grass carp keeps down the Azolla and finishes off the zeolite-treated human refuse. They're returning the residues from the essential oil still provided by AID to the soil. But not just any residue anywhere. Seems that back in 1985, Duke quit talking and computerized all that data showing which plants (and their residues) had positive effects like alfalfa on crop yields and which had negative effects on crops and weeds. Getting 3 MT of leaf protein from alfalfa left a lot of spent residue around, even after ethanol generation. Some of the triacontinol persisted even in these second generation residues, enough to boost the yields of tomatoes by 10 percent, beans by 15 percent. With the computerized systems analysis of the allelochemic insecticides and fungicidal, as well as insect-regulatory aspects of spent residues, there was real planning as to distribution of the allelopathic residues. The locals went all out on Vietmeyer's winged bean when they found germplasm for seeds resistant to bruchids. In the past, bruchids had consumed half of their stored grain. This minor discovery had the effect of doubling their yields of dry beans. Besides, they got more nitrogen fixed than from the haricot bean, and edible roots instead of poisonous roots.

Following up on McKell's suggestion back in 1980, the Magic Mountaineers are using native species in their multitiered agroecosystems. Ipecac, here, like ginseng to the north, only grows in the shade. The natives are using byproducts from their overstory tonka bean (coumarin producer *Dipteryx odorata*) to stimulate rooting of new cuttings of ipecac (*Cephaelis ipecacuanha*) as they harvest roots of the older ipecac. Coumarin has been shown to stimulate cuttings. Both these species, like shade-loving *Piper dariense* (used for toothache and fish poison), are adapted to the cooler, higher slopes of the Subtropical Montane Forests.

Gradually, tonka beans and oil-producing palms and diesel trees are being introduced into the forest canopy as other species are felled or die. Magic Mountaineers still don't believe Calvin's estimates that they can get 125 barrels of "diesel" per hectare from their "diesel trees," *Copaifera* spp., but the resin is now selling for $10 a kilo and they can harvest renewably a few hundred dollars worth a year as they are harvesting ipecac, chicle, rubber, ivorypalm, quinine, and tonka beans from TMF species over on Meyer's Mountain. The nature lovers still prefer to gather their items renewably from Meyer's Mountain National Forest, while the homebodies are transplanting their species as money-making trees for the upper story of their agroforestry enterprises.

One of the Magic Mountaineers was raising crocodiles for the export market in his water chestnut patch. If harvested young, they did not thrash around too much and mess up his water chestnuts.

However, the crocodiles did cut his fish and prawn yield by 50 percent. He had trouble getting his hides shipped directly to the United States Endangered species authorities thought that cultivating crocodiles might endanger them in the wild. Another Magic Mountaineer had been exporting butterflies to the United States until the endangered species people shut off the port. When the farmer abandoned his operation, two species went extinct, as far as Magic Mountain was concerned. Perhaps they still exist over on Meyer's Mountain. Another farmer was exporting amaranth seed to the U.S. health food market until the regulators stopped him, trying to avoid the importation of another weed. Boy Scouts back in the United States quietly filled this market by harvesting the amaranth seeds from weedy cornfields.

On the gravelly limestone ridge, where the 4 m annual rainfall quickly percolated through, some of Felker's Prosopis was doing well, but the natives still preferred the tamarinds (*Dialium, Tamarindus*). They tend to vary their diets with other legumes, some mentioned by Felker; Cassia, Enterolobium, Hymenaea, Inga, Parkia, Prosopis. The Prosopis yield of 12 MT/ha did not carry so much weight here in the humid tropics as it did back on the Chilean desert. One Chilean tree was reported to yield at the rate of 12,700 kg fruit/ha, clearly a good yield for the desert. But none of the Arid Tropical species compete well in the Humid Tropics and vice versa.

A cord of mesquite will yield 30 million Btu compared to 25 million Btu from a ton of coal. Arizona pinon-juniper yields 18 million Btu. And Magic Mountaineers, still cooking with wood, were impressed by Vietmeyer's statement that a hectare of Leucaena would yield 10 times as much wood as a well-managed pine plantation. The new fuel-efficient stoves the Swedes sent cut down on firewood consumption, leaving them with less ash to fertilize their vegetable plots.

Some of the natives of Magic Mountain are not fond of Leucaena, some of them even lamenting that they had sown it for cover on the old landslide. Its seeds were coming up everywhere, but it only seems to be a real weed on the scarp. Nitrogen is, after water, the most frequent limiting factor in the Tropics, so Leucaena is viewed by some as a good N source. Our Magic Mountaineers were impressed with Halliday's statement that biological nitrogen fixation is "economically more sound and environmentally more acceptable than nitrogen fertilizer use in agriculture" and his statistics; most legumes fix 100 kg/ha, with Leucaena at 350 kg/ha, and a potential of 800 kg/ha. Bill Liebhardt estimated Rhizobial Nitrogen fixation of pure strands of Leucaena at 50 to 900 kg/ha. Still, certain government agencies sent millions of dollars worth of N to the Third World, when appropriately inoculated legumes, cheaper to distribute, would have done the job renewably. Efficiency was the excuse, it takes less paperwork to spend $100 million at one fell swoop than to make 100 separate million dollar investments.

The Chinese on the steep slopes of the wet side of the mountain are intercropping azolla, rice, fish and duck, in their intricately terraced rice paddies. They were getting 15 MT rice per hectare as Clark had reported in 1980. They were not getting 150 MT dry weight of Azolla as suggested by Clark, but they had devised a system for raking off the bulk of the Azolla every 10 days, after it doubled its biomass, and adding the biomass as a mulch to truck gardens on the ferralsols. And they sell a lot of azolla-fed fish and ducks off their rice terraces. There is a persistent rumor that they are adding night soil to their rice-azolla farms. But their terraced slopes are as productive as the alluvial bottomland.

Duke had always pushed the sunchoke (sunflower × artichoke) as a biomass candidate for the temperate zone. The Chinese have squeezed it, like so many other temperate species, into the humid tropics. Sunchoke accomplished some of the things enthusiasts for perennial corn were pushing back in the 1980s. The roots are perennial and produce at least 20 MT/ha edible root, leaving behind more than enough to reseed itself and feed the last of the wild peccaries. The annual sunflower parent would have to be replanted but not the artichoke, it kept coming back like a song, more like a weed. One farmer who wishes to go into a different agrotechnology had to borrow the biocontrol pigs to clear his land of sunchokes. Chinese learned to add the raw artichoke to Chinese dishes to substitute for water chestnut. It also turns out that the aerial biomass, cut three or four times a year, was good for leaf protein and ethanol synthesis. Still this sunchoke did not yield as highly as some of the other scenarios. Some of the Magic Mountaineers accused Johnny Sunchokeseed of introducing a weed to the Tropics. Take it home, yankee.

Down in the swamps, the natives were producing closer to the lower than the upper predictions of DOE back in 1980, 60 to 270 barrels of ethanol per hectare from cattails. They were getting higher yields from some of the native swamp species Acrostichum, Dieffenbachia, Gynerium, Erythrina,

Montrichardia, Panicum and Pennisetum, species that DOE had not even considered.

Before Panama took over the canal, U.S. germplasm specialists provided many useful palms for trial on Magic Mountain. Finally the Orbignya from Brazil was bearing seed, but the smuggled seed had triggered an incident. Brazil broke relations with Panama and the United States for collecting germplasm without a permit. Back in the 1980s at a congressional OTA workshop, Duke had wondered about some of Schultes' optimistic numbers for *Orbignya martiana*: trees reported to yield more than a MT of fruit per year, 10 percent of which was kernel, 50 percent of which was oil for a yield of 40 kg oil per tree or a barrel of oil for every 4 trees, accompanied by 40 kg protein per tree and perhaps 350 kg carbohydrate per tree. Duke feared these projections were optimistic, like Melvin Calvin's estimates of gopherweed oil. Still he recommended that OTA urge investigation of all palms because many are adapted to marginal tropical habitats. Some of the Magic Mountaineers did get yields almost that high with trees at 100 to 200 trees per hectare. Above this, per-tree yields dropped off. Still, some of our Magic Mountaineers are getting 100 barrels of palm oil per hectare on marginal soils. There was almost as much protein, and more carbohydrates for ethanol production.

Magic Mountaineers had really been impressed with Mumpton's zeolites. Zeolites increased their fish biomass by 10 percent with 5 percent clinoptilolite, chicken feed efficiencies by 20 percent with 10 percent zeolite, beef profitability by 20 percent, calf growth by 20 percent with 5 percent zeolite, and swine growth by 25 to 30 percent with 5 percent clinoptilolite. They are using the clinoptilolite to treat feces in their portajohns, lessening the odor.

Zeolites have made a big difference in farming, too. The nitrogen is held longer after the zeolite is applied to the soil. Near Panama City, the zeolites were being imported from the interior to slowdown plant uptake of heavy metals in the sewage sludge energy farms and in the purification of low-Btu methane produced by anaerobic fermentation of beef excrement in the Hamburger Farm.

One oilpalm farmer with several dozen hectares persisted in grazing beef and milk cows in the partial shade of his oil palms and coconuts. He heard that he could increase his oil yields by 2 MT (about 6 barrels) per hectare simply by interplanting with tropical kudzu and butterfly pea. He found that by limited grazing, he could maintain his oil production. When asked what he was doing with his oil and cattle he said, "Those carnivorous Americans are still after our cheap hamburgers. Why at some joints you can get a centigrammer (centigram hamburger) for $2.00. Some people hint that it's laced with palm protein, one of our byproducts here. And the Americans are running their soybean farms with diesel tractors fueled with palmoil. That is considerably cheaper than soyoil." "And what about your milk?" "Oh, we dehydrate that and send it to the Americans too."

Office of Technology Assessmont

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